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Modeling of exploitation process of highway toll collection system

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ABSTRACT
Transport telematics systems integrate information technology with telecommunications applications for necessities of transport systems. The article presents the manual motorway toll system that is currently used in Poland for vehicles with the permissible laden weight below 3.5 tones. Then, an analysis of the operation process of manual toll collection systems is provided, taking into account the guidelines of the General Directorate for National Roads and Motorways in terms of reliability and exploitation.

KEYWORDS: maintenance, transport telematics, reliability

1. Introduction

The term "telematics" was introduced for the first time in French developments (French: télématique) in the early seventies of the twentieth century. It was coined using two French words: telecommunications (Fr. télécommunications) and information technology (Fr. informatique). In English terminology, it was used only at the end of the seventies of the twentieth century. At the beginning, this phrase was not used so often. Only the scientific and industrial works and projects in the field of telematics, announced and implemented to be executed by the European Union, resulted in starting to use them more often. This period dates back to the nineties of the twentieth century. Today, the term "Telematics" is used to describe a field of science integrating the telecommunications and IT solutions. Such solutions are applied everywhere, where they brings benefits, compared to the use of isolated solutions. It is possible because, among others, a synergy effect is achieved.

One of the areas, where the telematics solutions are used is transport [11,13,14]. Currently, it is one of the territorially largest and fastest growing scopes (both in Poland and in Europe, as well as in the world). The first developments in the field of transport telematics were published in Poland in the mid-nineties of the twentieth century.

Transport telematics is defined as a field of knowledge and technical activities integrating informatics with telecommunication [17,24,28], which is applied in the transportation systems. There are several areas, in which this concept functions:

- road telematics, including the highway [20,21] and urban ones,
- railway telematics,
- aircraft telematics [18,19,23,25],
- marine telematics.

The highway telematics means the use of various ICT systems on highways. The purpose of their implementation is to increase the travel and transport safety. Thus, a number of other beneficial properties occur, such as, among others, the reduction of environmental degradation [6], the increase in the transport processes efficiency [7,10], better use of the road infrastructure, obtaining more favourable economic results of the highway operators, etc.

The highway telematics systems consist of the management centre of transport, passenger traffic, vehicle traffic, and goods transfer, as well as vehicles (cars, buses, motorcycles, etc.). The intelligent transport telematics system, as well as the road, driver and transport service management subsystem based on the real-time telecommunication [27], constitute a logical sequence that allows to monitor and control the people, vehicles and goods movement in variable environmental conditions. One of the currently applied subsystems is a highway toll collection system.

Highway telematics systems operate in variable maintenance conditions [2,4,12,16]. As elements of the transport infrastructure, they should maintain usability. One of the key issues is to ensure the continuous operation of these systems at a certain level of implementation of the services offered to passengers (also including electromagnetic interference [3,22]). So far, the author has made a reliability and maintenance analysis of the selected systems [13]. Therefore, another important stage of the research is to conduct the reliability and maintenance analysis of highway toll collection systems with regard to the relations in them. By conducting this system's operation process modelling, it is possible to demonstrate the impact of the intensity of transitions between the distinguished states on selected maintenance parameters.

2. Highway toll collection system characteristics

One of the telematics services, which is offered by transport telematics systems, includes toll collection for the use of roads. It relates both to the use of roads (e.g. tolls for using highways), and to the use of parking spaces (e.g. car parks). In this paper, the particular attention was paid to the highway toll collection system. Currently, there are two systems in Poland [8]:

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

In the manual toll collection system, vehicles operators pay a toll for toll roads at the tollbooth. 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 highway,
- toll station (SOP), if it is located within the slip road.

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 (Eng. On Board Unit) 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.

In Fig. 1, a general view of the tollbooth was presented. Its composition includes:

- toll collection building (together with a lane traffic controller, an operating terminal integrated with a cash register, and a display for drivers),
- inductive loop,
- automatic barrier,
- signaller.

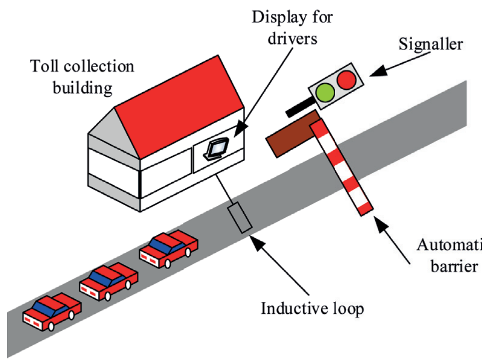

Fig. 1. A general view of the tool booth [own studies]

The toll collection process in the manual toll collection system is carried out as follows:

- a vehicle drawing up to the tollbooth is detected by the inductive loop
- the display for drivers informs about the amount of the toll,
- a collector using the operating terminal integrated with the cash register provides the toll confirmation,
- the signaller displays the signal about the possibility of leaving the tollbooth,
- a collector raises the automatic barrier to allow the vehicle to leave the tollbooth.

The toll collection process in the electronic toll collection system takes place automatically because the vehicle is fitted with the OBU transponder. It enables its wireless communication with devices that are installed on the toll collection system gates.

3. Reliability and maintenance analysis of the highway toll collection system

By conducting the analysis of the toll collection system functioning, which includes electronic and manual subsystems, it is possible to illustrate the relationships occurring in this system, in terms of the reliability [5,15] and maintenance [1,9,26], as it is presented in Fig.2.

The toll collection system should be treated as a unit of two subsystems: the electronic toll collection system (ESPO) and the manual toll collection system (MSPO). The damage to the electronic toll collection system results in the transition from the state of complete usability S_{PZ} to partial usability I, the one, in which the manual toll collection system operates (S_{ZB1}). The restoration of the state of usability of the electric toll collection system results in the transition from the state of partial usability I S_{ZB1} to the state of complete usability $S_{PZ.}$ If the system is in the S_{ZB1} state and the damage to the manual toll collection system causing suspension of its operation – the system changes into the state of unfitness S_B.

The damage to the manual toll collection system, as the first one, results in the transition from the state of complete usability S_{PZ} to the state of partial usability II S_{ZB2}. The restoration of the state of usability of the manual toll collection system results in the transition from the state of partial usability II S_{ZB2} to the state of complete usability $S_{PZ.}$ When the system is in the S_{ZB2} state and the damage to the electric toll collection system occurs, the transition to the state of unfitness S_B takes place.

The transition from the state of unfitness S_B to the state of complete usability S_{PZ} is also possible. Such an event occurs when the functioning of both toll collection subsystems, the electronic and manual ones, is restored.

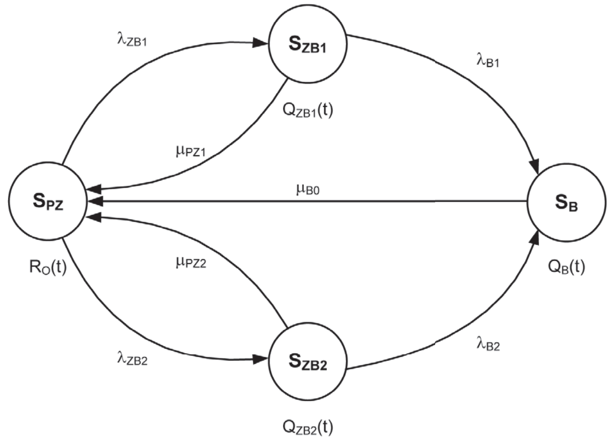

Fig. 2. Relations within the toll collection system [own studies]

Markings in Fig.:

$R_O(t)$ – the probability function of the system's staying in the state of usability,

$Q_{ZB1}(t)$ – the probability function of the system's staying in the state of partial usability I,

$Q_{ZB2}(t)$ – the probability function of the system's staying in the state of partial usability II,

$Q_B(t)$ – the probability function of the system's staying in the state of unfitness,

λ_{ZB1}, λ_{ZB2} – intensity of transitions from the state of complete usability to the state of partial usability,

$\mu_{PZ1,}$ μ_{PZ2} – intensity of transitions from the state of partial usability to the state of complete usability,

l_{B0} – intensity of transitions from the state of unfitness to the state of complete usability,

$l_{B1,}$ l_{B2} – intensity of transitions from the state of partial usability to the state of unfitness.

The system shown in Fig. 2 can be described by the following Chapman–Kolmogorov equations:

$$\begin{aligned}
R_0'(t) &= -\lambda_{ZB1} \cdot R_0(t) + \mu_{PZ1} \cdot Q_{ZB1}(t) - \lambda_{ZB2} \cdot R_0(t) + \mu_{PZ2} \cdot Q_{ZB2}(t) + \mu_{B0} \cdot Q_B(t) \\
Q_{ZB1}'(t) &= \lambda_{ZB1} \cdot R_0(t) - \mu_{PZ1} \cdot Q_{ZB1}(t) - \lambda_{B1} \cdot Q_{ZB1}(t) \\
Q_{ZB2}'(t) &= \lambda_{ZB2} \cdot R_0(t) - \mu_{PZ2} \cdot Q_{ZB2}(t) - \lambda_{B2} \cdot Q_{ZB2}(t) \\
Q_B'(t) &= \lambda_{B1} \cdot Q_{ZB1}(t) + \lambda_{B2} \cdot Q_{ZB2}(t) - \mu_{B0} \cdot Q_B(t)
\end{aligned} \tag{1}$$

Assuming baseline conditions:

$$\begin{aligned}
&R_0(0) = 1 \\
&Q_{ZB1}(0) = Q_{ZB2}(0) = Q_B(0) = 0
\end{aligned} \tag{2}$$

and applying the Laplace transform, the following system of linear equations is obtained:

$$\begin{aligned}
s \cdot R_0^*(s) - 1 &= -\lambda_{ZB1} \cdot R_0^*(s) + \mu_{PZ1} \cdot Q_{ZB1}^*(s) - \lambda_{ZB2} \cdot R_0^*(s) + \mu_{PZ2} \cdot Q_{ZB2}^*(s) + \mu_{B0} \cdot Q_B(t) \\
s \cdot Q_{ZB1}^*(s) &= \lambda_{ZB1} \cdot R_0^*(s) - \mu_{PZ1} \cdot Q_{ZB1}^*(s) - \lambda_{B1} \cdot Q_{ZB1}^*(s) \\
s \cdot Q_{ZB2}^*(s) &= \lambda_{ZB2} \cdot R_0^*(s) - \mu_{PZ2} \cdot Q_{ZB2}^*(s) - \lambda_{B2} \cdot Q_{ZB2}^*(s) \\
s \cdot Q_B^*(s) &= \lambda_{B1} \cdot Q_{ZB1}^*(s) + \lambda_{B2} \cdot Q_{ZB2}^*(s) - \mu_{B0} \cdot Q_B(t)
\end{aligned} \tag{3}$$

Transforming it, a record in the schematic view is obtained:

$$\begin{aligned}
R_0^*(s) &= -\frac{b_1 \cdot b_2 \cdot c}{b_2 \cdot c \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 \cdot c + b_1 \cdot c \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + b_2 \cdot \lambda_{B1} \cdot \mu_{B0} \cdot \lambda_{ZB1} + b_1 \cdot \mu_{B0} \cdot \lambda_{B2} \cdot \lambda_{ZB2}} \\
Q_{ZB1}^*(s) &= -\frac{b_2 \cdot c \cdot \lambda_{ZB1}}{b_2 \cdot c \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 \cdot c + b_1 \cdot c \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + b_2 \cdot \lambda_{B1} \cdot \mu_{B0} \cdot \lambda_{ZB1} + b_1 \cdot \mu_{B0} \cdot \lambda_{B2} \cdot \lambda_{ZB2}} \\
Q_{ZB2}^*(s) &= -\frac{b_1 \cdot c \cdot \lambda_{ZB2}}{b_2 \cdot c \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 \cdot c + b_1 \cdot c \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + b_2 \cdot \lambda_{B1} \cdot \mu_{B0} \cdot \lambda_{ZB1} + b_1 \cdot \mu_{B0} \cdot \lambda_{B2} \cdot \lambda_{ZB2}} \\
Q_B^*(s) &= -\frac{b_2 \cdot \lambda_{B1} \cdot \lambda_{ZB1} + b_1 \cdot \lambda_{B2} \cdot \lambda_{ZB2}}{b_2 \cdot c \cdot \lambda_{ZB1} \cdot \mu_{PZ1} - a \cdot b_1 \cdot b_2 \cdot c + b_1 \cdot c \cdot \lambda_{ZB2} \cdot \mu_{PZ2} + b_2 \cdot \lambda_{B1} \cdot \mu_{B0} \cdot \lambda_{ZB1} + b_1 \cdot \mu_{B0} \cdot \lambda_{B2} \cdot \lambda_{ZB2}}
\end{aligned} \tag{4}$$

where:

$$\begin{aligned}
a &= s + \lambda_{ZB1} + \lambda_{ZB2} \\
b_1 &= s + \mu_{PZ1} + \lambda_{B1} \\
b_2 &= s + \mu_{PZ2} + \lambda_{B2} \\
c &= s + \mu_{B0}
\end{aligned} \tag{5}$$

In the above outcome, the symbol „*" in markings and the symbol „s" in probabilities of the system's staying in the distinguished states R_O, Q_{ZB1}, Q_{ZB2}, Q_B, were omitted.

Conducting further mathematical analysis, the relationships which allow to determine the probabilities of the entire system's staying in the states of: complete usability S_{PZ}, partial usability S_{ZB1} and S_{ZB2} as well as unfitness S_B are obtained.

4. Modelling the reliability and maintenance process of the highway toll collection system

The simulation and computer methods as well as studies give an opportunity to determine an influence of the reliability and maintenance parameters of particular subsystems on the entire system's parameters relatively fast.

Thanks to the computer assistance, the calculations enabling determination of the probability of the system's staying in the state of complete usability R_O can be made. Such procedure is shown in the following example.

Example

Assuming the following values describing the analysed system:

- duration of research – 1 year (the value of this time is given in the units as hours [h]):
  t=8760 [h]
- intensity of transitions from the state of complete usability to the state of partial usability λ_{ZB1}:
  λ_{ZB1}=0,000001
- intensity of transitions from the state of complete usability to the state of partial usability λ_{ZB2}:
  λ_{ZB2}=0,0000001
- intensity of transitions from the state of partial usability to the state of unfitness λ_{B1}:
  λ_{B1}=0,0000001
- intensity of transitions from the state of partial usability to the state of unfitness λ_{B2}:
  λ_{B2}=0,000001
- intensity of transitions from the state of unfitness to the state of complete usability μ_{B0}:
  μ_{B0}=0,01

- intensity of transitions from the state of partial usability to the state of complete usability μ_{PZ1}:
$$\mu_{PZ1}=0,1$$
- intensity of transitions from the state of partial usability to the state of complete usability μ_{PZ2}:
$$\mu_{PZ2}=0,2$$

As result of the above input values using the system of equations (4), the following things are obtained:

$$R_0^*(s)=\frac{\begin{array}{l}1,10001\cdot 10^{12}\cdot s+1\cdot 10^{11}\cdot \mu_{PZ1}+1\cdot 10^{12}\cdot \mu_{PZ2}+1\cdot 10^{20}\cdot s^2\cdot \mu_{PZ1}+1\cdot 10^{20}\cdot s^2\cdot \mu_{PZ2}+\\ +1,00011\cdot 10^{18}\cdot s^2+1\cdot 10^{20}\cdot s^3+1,00001\cdot 10^{18}\cdot s\cdot \mu_{PZ1}+1,0001\cdot 10^{18}\cdot s\cdot \mu_{PZ2}+\\ +1\cdot 10^{18}\cdot \mu_{PZ1}\cdot \mu_{PZ2}+1\cdot 10^{20}\cdot s\cdot \mu_{PZ1}\cdot \mu_{PZ2}+100000\end{array}}{\begin{array}{l}1,110011\cdot 10^{6}\cdot s+1,00011\cdot 10^{18}\cdot s^2\cdot \mu_{PZ1}+1,00011\cdot 10^{18}\cdot s^2\cdot \mu_{PZ2}+1\cdot 10^{20}\cdot s^3\cdot \mu_{PZ1}+\\ +1\cdot 10^{20}\cdot s^3\cdot \mu_{PZ2}+2,200131\cdot 10^{12}\cdot s^2+1,00022\cdot 10^{18}\cdot s^3+1\cdot 10^{20}\cdot s^4+\\ +1,10001\cdot 10^{12}\cdot s\cdot \mu_{PZ1}+1,10001\cdot 10^{12}\cdot s\cdot \mu_{PZ2}+1\cdot 10^{18}\cdot s\cdot \mu_{PZ1}\cdot \mu_{PZ2}+\\ +1\cdot 10^{20}\cdot s^2\cdot \mu_{PZ1}\cdot \mu_{PZ2}\end{array}}$$

As a result of transformations, it is possible to obtain:

$$R_0(t)=1.6373934\cdot e^{-0.01\cdot e\text{-}8\cdot t}+0.000004999979\cdot e^{-\cdot 0.2000011\cdot t}+$$
$$+9.9995788985\cdot e^{-0.100001099998\cdot t}+0.9999939998985$$

As a final result, the following things are achieved: R_o=0,999993999.

5. Conclusion

In this paper, the reliability and maintenance analysis of the highway toll collection system was presented. Two subsystems, such as electronic and manual toll collection systems, were taken into consideration. The conducted mathematical analysis (in the considerations of which the following states were adopted: the state of complete usability R_0, the state of partial usability Q_{ZB1}, the state of partial usability Q_{ZB2} and the state of unfitness Q_B as well as certain transitions between them), allowed to determine the probabilities of the system's staying in the above mentioned states. The obtained relationships allow to analyse the impact of particular intensities of transitions on values of the determined probabilities. Therefore, it enables to control the operation process of these systems. Within further studies, it is planned to take into consideration the financial expenditure earmarked for periodic inspections and their influence on the probability of the system's staying in the state of its usability.

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