# Reliability Models for a Safe Train Traffic Control Systems Accounting the Railway Infrastructure States

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***Abstract*—The authors developed the advanced train traffic control system architecture. This architecture is based on the railway infrastructure facilities monitoring techniques integrated into the railway automation and remote-control equipment. Such system has a higher level of safety due to the transferring data about the infrastructure facilities state into control complexes directly without the "human – operator" link of the monitoring system. Data from infrastructure facilities that do not directly interact with railway automation equipment's make it possible to quickly develop control actions for the timely developing defects counteract. The authors developed reliability models for the train traffic control systems, in which the railway infrastructure facilities states are considered. Authors presents the accounting the infrastructure complex safe state relevance in train traffic control systems. The developed reliability models using are advisable in the safe train traffic control systems development, as well as in railway infrastructure facilities digital twins developing include real-time modeling of processes.**

***Keywords*—train traffic control, train traffic safety, railway automation and remote-control systems, monitoring systems for engineering structures and facilities, train traffic control system reliability model***

## I. Introduction

The equipment and control systems for critical technological processes are implemented in accordance with the specified requirements for reliability and safety of operation. This fully applies to the railway complex. However, pre-failure and failures cannot be ruled out during the operation of such a complex like a railway transport system, where a huge number of participants are involved in the transportation process, including technical facilities and operators like a train dispatcher, station attendants, cabin drivers, service departments, etc. Some of them pose a threat to the train traffic safety. The final links in the chain of the transportation process, from the train traffic safety point of view, are the railway automation and remote-control technical equipment's [1]. They allow to control remotely train traffic and wayside equipment on stations and hauls, beside allow the command transmission to cabin driver through the transferring data by traffic lights. Railway automation and remote-control equipment are implemented in accordance with certain safety concepts that are established in accordance with regulatory documents. For example, on the Russian Railways for microelectronic automation and remote-control systems development methods and principles for ensuring safety are established in [2].

Nevertheless, the railway automation and remote-control technical means are implemented as safe, but do not include the changing states of railway infrastructure facilities during operation, which do not directly affect them [3]. That is why such situations are not excluded during the operation of the railway transport system, in which the presence of a dangerous defect in an artificial structure (for example, the obstruction clearance violation [4]) does not cause the inclusion of a prohibited indication at the traffic light enclosing the corresponding section. Moreover, in this case, it is impossible to give a prohibiting indication in the railway automation and remote-control system even manually (apart from barrage signaling equipment).

In order to increase fault tolerance, railway infrastructure equipment are subjected to diagnostic procedures at predetermined intervals using both manual and automated means. These include wearable diagnostic tools as well as permanently installed monitoring equipment. Not many facilities are currently equipped with the latter. The choice of an object for monitoring is determined by the presence of an unacceptable risk to the train traffic safety.

It is safety-critical necessity to provide the monitoring systems integration into the train traffic control systems for railway infrastructure equipment, which are being gradual developed and settlement into operation [5 – 13]. The diagnostic and monitoring equipment integration features into the railway automation and remote-control systems are described in [3].

This paper is devoted to the safe train traffic control system reliability models development, which implies the technical integration monitoring permanently installed means into railway infrastructure equipment.

## II. THE SAFE TRAIN CONTROL SYSTEM ARCHITECTURE

Figure 1 demonstrate the safe train traffic control system architecture developed by the paper authors, in which the control subsystem and the monitoring subsystem are distinguished, and the concept of this architecture is described in [3]. In the monitoring subsystem, there is a division into a subsystem for monitoring railway automation and remote-control equipment and a subsystem for monitoring railway infrastructure facilities (subsystems to which functional safety requirements apply are highlighted in color).

Currently, infrastructure monitoring systems are implemented separately from railway automation and remote-control systems, monitoring systems are also separately implemented in other railway transport departments [12, 13] (this is mainly data from portable monitoring tools, while permanently installed monitoring systems can also be used) [5, 10, 11]. However, for a reliable diagnosis, genesis, and prognosis, it is necessary to consider the monitoring data full set on all infrastructure technical condition, and not just individual ones (for example, from monitoring systems for railway automation and remote-control equipment. In addition, at present, monitoring systems are not interacted with the railway automation and remote-control systems: neither with the feedback circuit using, nor as an indication means. Similar methods in the nearest train traffic control systems development are also not implied [14, 15]. Historically, railway automation and remote-control systems were not (and were not planned) endowed with built-in measuring and automatically analyzing diagnostic data equipment [1].

Fig. 1 demonstrate the advanced railway automation and remote-control system architecture, in which, based on the results monitoring data, it is possible to determine the conditions for the transition to certain protective states, both for the signaling, interlocking, and blocking equipment, and for other railway infrastructure. At the same time, the regulatory framework for the implementation of such a system should be determined, since severe restrictions are applied to the railway automation and remote-control systems in towards to functional safety [1, 16]. For this reason, restrictions of this kind should be applied both to permanently installed monitoring systems that are in operation or under development, and to the intelligent data processing results of monitoring.

## III. THE TRAIN TRAFFIC CONTROL SYSTEM STATE GRAPH

Railway automation and remote-control equipment and systems can simultaneously be in only one of the states: serviceable; operable; operable but pre-failure; inoperable but in protective; non-serviceable dangerous or limit behavior (in this case, the limit behavior state equal the depths of object non-serviceable, it can be both protective and dangerous). This classification concerns only equipment and systems of railway automation and remote-control, as closed-loop control systems.

By integrating the safe entity-relationship of stationary monitoring systems with railway automation and remote-control systems at the synthesis stage (for a start, conceptually), additional states of the train traffic control system are introduced into consideration.

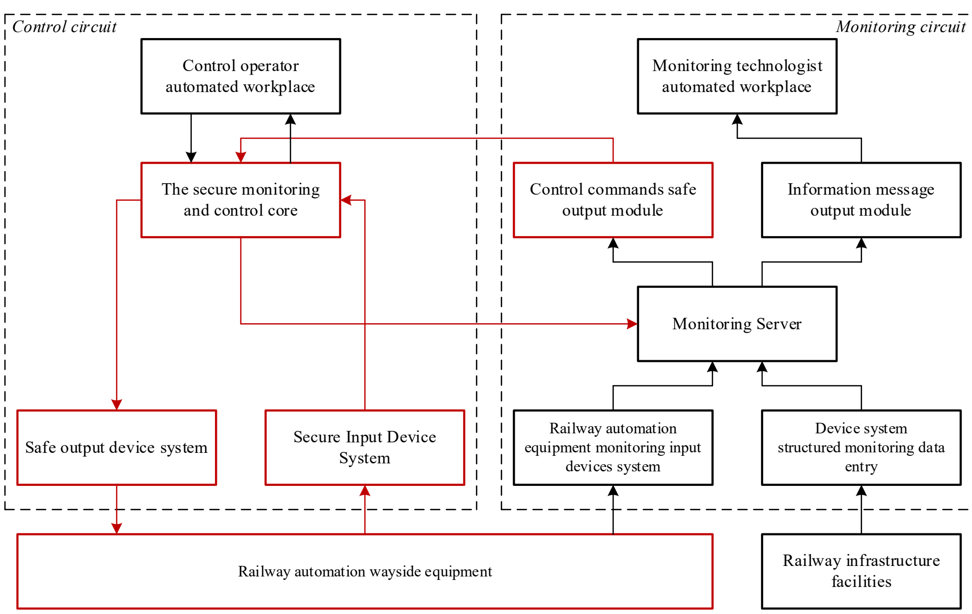


Fig. 1. The safe train traffic control system architecture.

Such states are determined based on data on the railway infrastructure objects, and not classically only based on data on the railway automation and remote-control equipment. Let single out two such states: protective and dangerous states.

Let introduce the train traffic control system states notation: $S_0$ – serviceable; $S_1$ – operable; $S_2$ – operable, but pre-failure; $S_3$ – inoperable, but in protective; $S_4$ – inoperable, but in dangerous; $S_5$ – protective, corresponding to the infrastructure object fault; $S_6$ – dangerous, corresponding to the infrastructure object fault.

The $S_0$ – $S_4$ states correspond to the states which generated by the train traffic control system (railway automation and remote-control system) based on control, monitoring, and the automatic data analysis results from monitoring devices. The $S_5$ and $S_6$ states correspond to inoperable states (or partial operability) of railway infrastructure facilities. In well-known studies, for example, [17], states $S_5$ and $S_6$ do not appear in any way, since the author does not consider interaction with railway infrastructure monitoring systems.

Let introduce into consideration the transient intensity train control system ($\lambda_{ij}$ and $\mu_{ji}$) from the state $S_i$ to the state $S_j$ and vice versa, while $\lambda_{ij}$ is the intensity associated with the system performance deterioration, and µji is the intensity associated with the performance improvement. For each $\lambda_{ij}$ $i < j$. For each $\mu_{ij}$ $i > j$. The values $\lambda_{ij}$ and µji are calculated from the statistical data on the operation of a specific railway infrastructure facility within the station and/or block.

Fig. 2 demonstrates a state graph of a train traffic control system, in which a subgraph is highlighted corresponding to transitions to additional states $S_5$ and $S_6$. The graph is incomplete, and some transitions are excluded.

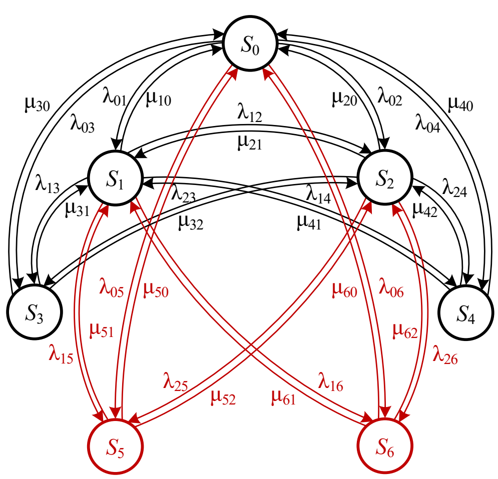


Fig. 2. Scenarios for the queue's formation at a two-way elevated overpass.

## IV. THE TRAIN TRAFFIC CONTROL SYSTEM RELIABILITY MODELS

Let assuming that the processes occurring in the system are Markov random processes. This allows, according to the graph in Fig. 2 to obtain the A. N. Kolmogorov equations system, the formation principles of which are described in [18]:

$$\begin{cases} \frac{\partial P_0(t)}{\partial t} = \mu_{10}P_1(t) + \mu_{20}P_2(t) + \mu_{30}P_3(t) + \mu_{40}P_4(t) + \mu_{50}P_5(t) + \mu_{60}P_6(t) - \\ -(\lambda_{01} + \lambda_{02} + \lambda_{03} + \lambda_{04} + \lambda_{05} + \lambda_{06})P_0(t); \\ \frac{\partial P_1(t)}{\partial t} = \lambda_{01}P_0(t) + \mu_{31}P_3(t) + \mu_{41}P_4(t) + \mu_{21}P_2(t) + \mu_{51}P_5(t) + \mu_{61}P_6(t) - \\ -(\mu_{10} + \lambda_{13} + \lambda_{12} + \lambda_{14} + \lambda_{15} + \lambda_{16})P_1(t); \\ \frac{\partial P_2(t)}{\partial t} = \lambda_{02}P_0(t) + \lambda_{12}P_1(t) + \mu_{42}P_4(t) + \mu_{32}P_3(t) + \mu_{52}P_5(t) + \mu_{62}P_6(t) - \\ -(\mu_{20} + \mu_{21} + \lambda_{23} + \lambda_{24} + \lambda_{25} + \lambda_{26})P_2(t); \\ \frac{\partial P_3(t)}{\partial t} = \lambda_{03}P_0(t) + \lambda_{13}P_1(t) + \lambda_{23}P_2(t) - (\mu_{30} + \mu_{31} + \mu_{32})P_3(t); \\ \frac{\partial P_4(t)}{\partial t} = \lambda_{04}P_0(t) + \lambda_{14}P_1(t) + \lambda_{24}P_2(t) - (\mu_{40} + \mu_{41} + \mu_{42})P_4(t); \\ \frac{\partial P_5(t)}{\partial t} = \lambda_{05}P_0(t) + \lambda_{15}P_1(t) + \lambda_{25}P_2(t) - (\mu_{50} + \mu_{51} + \mu_{52})P_5(t); \\ \frac{\partial P_6(t)}{\partial t} = \lambda_{06}P_0(t) + \lambda_{16}P_1(t) + \lambda_{26}P_2(t) - (\mu_{60} + \mu_{61} + \mu_{62})P_6(t). \end{cases} \quad (1)$$

System (1) is supplemented by the normalization equation:

$$\sum_{i=1}^{6} \frac{\partial P_i(t)}{\partial t} = 1. \quad (2)$$

For $t \to \infty$ the following limit theorem of A. A. Markov [18] holds: *if all intensities of event flows are constant, and the state graph is such that one can go from each state to each other in a finite number of steps, then the limit probabilities of states exist and do not depend on the initial state of the system.*

Analysis of the graph in Fig. 2 allows to conclude that the Markov theorem is applicable to the system under consideration. According to this theorem:

$$\lim_{t \to \infty} \frac{\partial P_i(t)}{\partial t} = 0,\ i = \overline{0,6}. \quad (3)$$

Using (3) and (2), rewrite system (1) in the form:

$$\begin{cases} \mu_{10}P_1(t) + \mu_{20}P_2(t) + \mu_{30}P_3(t) + \mu_{40}P_4(t) + \mu_{50}P_5(t) + \mu_{60}P_6(t) - \\ -(\lambda_{01} + \lambda_{02} + \lambda_{03} + \lambda_{04} + \lambda_{05} + \lambda_{06})P_0(t) = 0; \\ \lambda_{01}P_0(t) + \mu_{31}P_3(t) + \mu_{41}P_4(t) + \mu_{21}P_2(t) + \mu_{51}P_5(t) + \mu_{61}P_6(t) - \\ -(\mu_{10} + \lambda_{13} + \lambda_{12} + \lambda_{14} + \lambda_{15} + \lambda_{16})P_1(t) = 0; \\ \lambda_{02}P_0(t) + \lambda_{12}P_1(t) + \mu_{42}P_4(t) + \mu_{32}P_3(t) + \mu_{52}P_5(t) + \mu_{62}P_6(t) - \\ -(\mu_{20} + \mu_{21} + \lambda_{23} + \lambda_{24} + \lambda_{25} + \lambda_{26})P_2 = 0; \\ \lambda_{03}P_0(t) + \lambda_{13}P_1(t) + \lambda_{23}P_2(t) - (\mu_{30} + \mu_{31} + \mu_{32})P_3(t) = 0; \\ \lambda_{04}P_0(t) + \lambda_{14}P_1(t) + \lambda_{24}P_2(t) - (\mu_{40} + \mu_{41} + \mu_{42})P_4(t) = 0; \\ \lambda_{05}P_0(t) + \lambda_{15}P_1(t) + \lambda_{25}P_2(t) - (\mu_{50} + \mu_{51} + \mu_{52})P_5(t) = 0; \\ \lambda_{06}P_0(t) + \lambda_{16}P_1(t) + \lambda_{26}P_2(t) - (\mu_{60} + \mu_{61} + \mu_{62})P_6(t) = 0; \\ P_0(t) + P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t) + P_6(t) = 1. \end{cases} \quad (4)$$

System (4) is solved by any of the known methods.

Having discarded one of the system (4) equations (except for the normalization one), pass to the matrix form:

$$A=\begin{pmatrix}\lambda_{01} & -\mu_{10}-\lambda_{13}-\lambda_{12}-\lambda_{14}-\lambda_{15}-\lambda_{16} & \mu_{21} & \mu_{31} & \mu_{41} & \mu_{51} & \mu_{61} & \vline & 0\\ \lambda_{02} & \lambda_{12} & -\mu_{20}-\mu_{21}-\lambda_{23}-\lambda_{24}-\lambda_{25}-\lambda_{26} & \mu_{32} & \mu_{42} & \mu_{52} & \mu_{62} & \vline & 0\\ \lambda_{03} & \lambda_{13} & \lambda_{23} & -\mu_{30}-\mu_{31}-\mu_{32} & 0 & 0 & 0 & \vline & 0\\ \lambda_{04} & \lambda_{14} & \lambda_{24} & 0 & -\mu_{40}-\mu_{41}-\mu_{42} & 0 & 0 & \vline & 0\\ \lambda_{05} & \lambda_{15} & \lambda_{25} & 0 & 0 & -\mu_{50}-\mu_{51}-\mu_{52} & 0 & \vline & 0\\ \lambda_{06} & \lambda_{16} & \lambda_{26} & 0 & 0 & 0 & -\mu_{60}-\mu_{61}-\mu_{62} & \vline & 0\\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & \vline & 1\end{pmatrix}. \quad (5)$$

Denote by $A_i$ the matrices in which the *i-th* column is replaced by the column of free terms, and by $\Delta$ and $\Delta i$ – the matrix determinant $A$ and $A_i$. Then Cramer's method can be used to obtain the values:

$$P_i(t)=\frac{\Delta_i}{\Delta},\ i=\overline{0,6}. \quad (6)$$

In practice, it is quite difficult to obtain the transitions intensities values between the train traffic control system states especially regarding transitions to dangerous states. Therefore, simulation modeling is required. Statistical data can be obtained just using monitoring tools during operation over a sufficiently large time interval.

For the model in Fig. 2, the transitions probabilities from the state $S_i$ to the state $S_j$ and vice versa can be specified. Then the reliability model can be specified using the transition probabilities matrix and the initial probabilities vector. For the graph in Fig. 2, is given by:

$$P_{ij}(t)=\begin{vmatrix}p_{00} & p_{01} & p_{02} & p_{03} & p_{04} & p_{05} & p_{06}\\ p_{10} & p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16}\\ p_{20} & p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26}\\ p_{30} & p_{31} & p_{32} & p_{33} & 0 & 0 & 0\\ p_{40} & p_{41} & p_{42} & 0 & p_{44} & 0 & 0\\ p_{50} & p_{51} & p_{52} & 0 & 0 & p_{55} & 0\\ p_{60} & p_{61} & p_{62} & 0 & 0 & 0 & p_{66}\end{vmatrix}. \quad (7)$$

The initial probabilities vector is given by:

$$P_i(0)=\left(P_0(0),P_1(0),P_2(0),P_3(0),P_4(0),P_5(0),P_6(0)\right). \quad (8)$$

For example, in [17], the authors use numerical data obtained as a result of the railway track operation in one of the track sections in the Republic of Kazakhstan to solve a similar problem for assessing the track superstructure state (however, without permanent monitoring equipment coupling).

In practice, the above reliability models using requires the statistical data availability on the infrastructure facilities operation on the considered section of the railway – this can be either an assessment within the station and adjacent spans, or an assessment within a certain section of the railway line. Naturally, the data will be very different for stations and hauls with different technical equipment, depleted resource, and workload.

## V. Experiment

In the experiment, there was no binding to a specific section of the railway, and the transition matrix and the initial state vector were set arbitrarily:

$$P_{ij}(t)=\begin{vmatrix}0.3 & 0.3 & 0.2 & 0.1 & 0.01 & 0.08 & 0.01\\ 0.2 & 0.48 & 0.05 & 0.1 & 0.01 & 0.15 & 0.01\\ 0.2 & 0.38 & 0.05 & 0.2 & 0.01 & 0.15 & 0.01\\ 0.2 & 0.69 & 0.01 & 0.1 & 0 & 0 & 0\\ 0.2 & 0.74 & 0.01 & 0 & 0.05 & 0 & 0\\ 0.2 & 0.69 & 0.01 & 0 & 0 & 0.1 & 0\\ 0.2 & 0.74 & 0.01 & 0 & 0 & 0 & 0.05\end{vmatrix},$$

$$P_i(0)=(1,0,0,0,0,0,0).$$

Using the Markov chain calculator [19], a simulation of the operation of the system described by the graph in Fig. 1 was carried out. 2, with the selected initial data. The steady state vector obtained at the third step has the following form:

$$P_i(0)=(0.22,\ 0.48,\ 0.07,\ 0.1,\ 0.01,\ 0.11,\ 0.01).$$

For real examples, other values will be obtained, since in practice the transitions probabilities to dangerous states are extremely small. For example, for devices and train control systems, the dangerous failure rates, according to [2], are in the range $\lambda=10^{-8}\ ...\ 10^{-14}\ {}^{1}\!/_{h}$.

Modeling data can be refined using existing stationary and portable monitoring and technical diagnostic tools, and the operation process itself will be described by constantly changing data on the infrastructure facilities technical condition.

## VI. Conclusion

Train traffic control systems and permanent installation monitoring systems technical coupling with the control actions development for traffic control equipment can significantly increase the railway transport system safety level. However, at the same time, certain limitations are imposed on the monitoring system itself, related to the generation reliability of one or another information message based on the results of monitoring data analysis. As noted earlier [3], in practice this value should be normalized, and the monitoring systems themselves should be certified for compliance with safety integrity levels. The introduction at the stage of the railway automation and remote-control system synthesis of additional states associated with the transition to protective and dangerous states of critical railway infrastructure objects (directly affecting the safety of the transportation process) makes it possible to foresee in the control system possible reactions to a decrease in safety indicators and the development of a protective impact.

The safe train traffic control systems reliability models presented in the paper make it possible to estimate the transition probability to one state or another at each operation stage. Their use as part of digital models of railway stations, tracks and entire lines could be especially effective if properly equipped with technical monitoring tools.

Further research may be related to the study of the railway automation systems implementation features on a programmable element base using coupling with monitoring equipment, the requirements formation for the safe implementation of the "monitoring function" and the monitoring systems themselves, as well as simulation modeling of railway transport systems with an assessment of the impact of using the results monitoring for automatic impact on road users.

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