Reliability forecasting for optimal planning of measures for maintenance of security systems of transport infrastructure facilities

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Abstract. The paper studies the methods for predicting the reliability of technical security equipment located at transport infrastructure facilities. The methods of determining the probability of the state of readiness of technical systems with various combinations of parameters of the maintenance system are considered. The automation capabilities are demonstrated in the study of the effectiveness of technical security equipment based on the analysis of their tactical and technical characteristics.

1. Introduction

The concept of countering terrorism in the Russian Federation as one of the main tasks defines ensuring the safety of citizens and the anti-terrorism protection of potential targets of terrorist attacks, including critical infrastructure and life support facilities, as well as crowded places. Transport infrastructure facilities fully comply with the above criteria. The most serious terrorist acts of recent times occur in transport or are somehow related to transport.

In matters of anti-terrorism security, as a rule, its main components are the technical equipment of transport infrastructure facilities, providing them with high-quality security systems, and the reliability of security systems play a crucial role here. The reliability of the security system of the protected object of the transport infrastructure determines the ability to detect with a given probability and counteract the unauthorized actions of the offender in the framework of the project threat for a given time [1-9]. Designing and implementing a reliable security system structure at a protected facility is a complex scientific and practical task, which depends on a wide range of various factors.

2. Materials and methods

The mathematical apparatus of probability theory and optimal control can be considered as one of the possible solutions to this problem.

2.1 Problem statement

The effectiveness of the security system of the i-th section of the perimeter of some protected object in transport is determined by the probability of reliable detection of the intruder, which is calculated by the formula:
\[ F_i = P_{NP} \cdot K_{CCa} \cdot \prod_{j=1}^{3} \left( \gamma_j \cdot P_{DO_j} \right) \cdot K_{DA} \cdot K_{AH} \cdot K_{ICOH}, \tag{1} \]

where \( K_{CCa}, K_{AH}, K_{DA}, K_{ICOH} \) - readiness coefficients of equipment of the system for collecting and processing information, communication lines “sensors - station equipment”, communication lines “station equipment - response group”, engineering security equipment, respectively; \( P_{DO_1}, P_{DO_2}, P_{DO_3} \) - probabilities of detecting the intruder by technical means when trying to overcome the perimeter by climbing over the fence, by destroying the fence, by digging, respectively, \( \gamma_j, j = 1, 3 \), - the probability of attempts to commit the violation by appropriate methods; \( P_{NP} \) - probability of guaranteed prevention of violation by the response group.

To determine the reliability characteristics of a system in a long-term use, taking into account its reliability and recoverability, the probability of its normal functioning is used - the general reliability, which can be calculated by a simplified formula:

\[ P_N(t) = P_0 P(t), \tag{2} \]

where \( P_0 \) - the probability of the system being in good condition at the initial moment of time (equal to the value of the readiness coefficient \( K_g \)); \( P(t) \) - the probability of system uptime by a given time \([10-14]\).

To calculate the failure rate, use the relation

\[ \dot{\lambda} = \frac{1}{T_0}, \]

where \( T_0 \) - time to failure (hours) \( \dot{\lambda} \) – the value of the probability of failure, 1 / h.

The value of the probability of failure for the period of operation is found from the ratio:

\[ Q = \lambda t, \]

where \( t \) is the operating time (hours).

The probability of failure-free operation by a given time is determined by the formula:

\[ P = e^{-\lambda t}. \]

Let’s look at the technical means, the characteristics of which are presented in table 1.

| Technical means   | Model 1 | Model 2 |
|-------------------|---------|---------|
| Service life of the system, years | 10      | 10      |
| Time to failure, hour    | 60000   | 438000  |

Using automation capabilities significantly reduces the complexity of calculating the reliability indicators of technical systems. For automated calculation and prediction of the reliability of a technical system, an application was developed in Microsoft Visual Studio IDE (Figure 1).
The results of calculations of reliability indicators of technical means are summarized in tables 2, 3.

**Table 2.** Reliability indicators technical means (Model 1).

| Service life, years | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|---------------------|------|------|------|------|------|------|------|------|------|------|
| Time to failure, $T_0$, hours | 60000 |      |      |      |      |      |      |      |      |      |
| Failure rate, $\lambda$ | 1.66667e-05 |      |      |      |      |      |      |      |      |      |
| Characteristics of failures, $Q$ | 0.146 0.292 0.438 0.584 0.73 0.876 1.022 1.186 1.314 1.46 |      |      |      |      |      |      |      |      |      |
| Probability of failure-free operation, $P$ | 0.8642 0.7468 0.64530.55770.48190.41650.35990.31090.2687 0.2324 |      |      |      |      |      |      |      |      |      |

For illustrative purpose, we will display the obtained values of the calculation results on the graph (Figure 2). The graph clearly demonstrates that the reliability of the 2nd technical tool (model 2) does not fall below a predetermined level of 0.8 throughout the entire operating time; the reliability of model 1 becomes below the level of 0.8 after the first year of operation, and after the sixth year of operation, the probability of failure becomes more than one, which justifies the need to replace parts of the equipment, starting from the first year of operation, and a complete replacement in the sixth year.

**Figure 1.** Application user interface.
The above calculations show the need to take into account the requirements for the reliability of the technical means of the security systems of protected objects based not only on its declared service lives, but also on the basis of mathematical modeling and prediction of reliable characteristics in the future, which allows, inter alia, formulating such requirements for the characteristics of technical means, which will provide the necessary level of reliability of the technical system.

Among the main causes of technical failures of security equipment, it is possible to distinguish excess of the level of depreciation of fixed assets and the exhaustion of design resources of equipment, an increase in the complexity of equipment, causing a large number of structural elements, an increase in the intensity of operating modes, poor or inappropriate operating conditions, increased requirements for quality, accuracy and durability, increase in the level of responsibility of the functions performed.

Operation is the most critical period in the life cycle of any technical system. At this stage, the system experiences loads of various kinds and is under the influence of external conditions [14]. This process is continuous and requires scheduled and regular monitoring of the state of the system as a whole and its constituent elements in particular. The purpose of such impacts on the system is to ensure its working condition and a high level of operational reliability achieved when solving two main problems - ensuring normal operation of the elements and the system as a whole, predicting the life of individual components, and assigning optimal operating procedures.

When constructing models of the functioning of systems with various types of maintenance, a number of characteristic groups of flows (transitions from one state to another) are distinguished [14]: the occurrence of failures and malfunctions, the elimination of failures and malfunctions, sending an object for various types of maintenance, the removal from the states of technical maintenance service, etc. Markov approximation of transition processes is possible if random flows are the simplest and satisfy the conditions of ordinariness, stationarity and the absence of consequences [14].

In most applied problems, the use of Markov approximation usually does not exceed 3-5% [14]. Therefore, the use of the properties of Markov processes to solve practical problems of the reliability of security systems is justified.

Determining the optimal parameters of the maintenance system of the technical system is determined by its type and complexity, the characteristics of the functions performed, the number and type of probable states, the characteristics of the consequences of failures, as well as the operation and maintenance strategy.

2.2. Solution method. Probabilities calculation

Consider the simplest case of an object continuously monitored during exploitation (Figure 3), where 0 is an operable state, 1 is a failure.
Figure 3. State graph of a non-reserved object with restorations.

Two states are possible: operational and failure. At a known failure rate \( \lambda \), the model of the maintenance system contains a single control parameter - the average recovery time \( T_R \) or recovery rate \( \mu \), where \( T_R = 1/\mu \).

For the case of a steady-state operating mode \((t \to \infty)\), the system of equations describing the probabilities of the state of the object \( P_0(t) \), \( P_1(t) \) is reduced to a system of algebraic equations with respect to the final probabilities \( P_0 \) and \( P_1 \):

\[
\begin{align*}
-\lambda P_0 + \mu P_1 &= 0, \\
-\mu P_1 + \lambda P_0 &= 0
\end{align*}
\]

Knowing the failure rate \( \lambda \) and reliability level \( P_0 \) - the probability of the object being ready for work, or the probability \( Q = P_1 = 1 - P_0 \), we can determine the limit value of the average recovery time of the object, which means we can determine the parameters of the maintenance system.

In more complex cases, when solving optimization problems, some additional characteristics are determined that cannot be set on the basis of experimental studies or practice of operating the object. To solve such problems, the basic properties of Markov processes with continuous time are used [14].

Let’s consider a more complex model of an unreserved object with periodic maintenance (Figure 4). We introduce the following notation: 1 — operational state (readiness for work); 2 - maintenance; 3 - hidden failure (prior to maintenance).

Three states of the system are possible, as well as transitions of four types (table 4):

| Table 4. Types of transitions. |
|--------------------------------|
| **Transition №** | **Spacing** |
|---|---|
| 1 | from a healthy state (or a state of readiness for use) 1 to a maintenance state 2 with a frequency of \( t_{T0} \) with a magnitude of transition intensity \( \lambda_{12} = 1/t_{T0} \); |
| 2 | from ready state 1 to failure state 3 with a transition rate equal to the failure rate \( \lambda \) (or the failure parameter): \( \lambda_{13} = \lambda \); |
| 3 | from maintenance state 2 to ready state 1 with an intensity that is determined by the duration of maintenance \( t_{T0} \): \( \lambda_{21} = 1/t_{T0} \); |
| 4 | from the state of failure 3 to the state of maintenance 2 (transition due to the detection of a latent failure during maintenance) with the intensity of transitions \( \lambda_{32} \). |
The only workable state of a technical object is the state of readiness for work 1, in connection with which the main indicator of reliability is the probability of this state \( P_1 \), when analyzing technical risk, the main parameter is the probability of failure \( Q = P_3 \).

Parameters \( t_{TO}, \lambda, \tau_{TO} \), transition intensities \( \lambda_{12}, \lambda_{13}, \lambda_{21} \) can be determined by the test results or set by the maintenance schedule, and therefore, when building the model, we consider them known. To find the unknown intensity of transitions \( \lambda_{32} \), we use the properties of Markov processes with continuous time [10]. Since transition 3-2 is the only one \( P_{32} = 1, \ t_3 = t_{TO} - t_{13}, \ t_{13} = t_1 \). Then

\[
\lambda_{32} = \frac{P_{32}}{t_3} = \frac{1}{t_3} = \frac{1}{t_{TO} - t_{13}} = \frac{1}{t_{TO} - t_1}
\]  

(4)

At the same time \( \lambda_1 = \lambda_{12} + \lambda_{13} = t_{TO} \) and in the simplest case of failure rate:

\[
t_1 = \int_0^\infty (1 - F_1(t)) dt = \int_0^\infty e^{-\lambda t} dt = \int_0^\infty \left( 1 + t_{TO} \right) e^{-t_{TO} \lambda} dt = \frac{1}{\lambda + t_{TO}}
\]  

(5)

Then

\[
t_3 = t_{TO} - t_1 = t_{TO} - \frac{1}{\lambda + t_{TO}}
\]  

(6)

Taking account of (4)

\[
\lambda_{32} = \frac{1}{t_{TO} - \frac{1}{\lambda + t_{TO}}} = \frac{1 + \lambda t_{TO}}{\lambda t_{TO}^2}
\]  

(7)

The system of differential equations corresponding to the oriented state graph shown in Figure 4 has the form:

\[
\begin{align*}
\frac{dP_1(t)}{dt} &= -(\lambda_{12} + \lambda_{13})P_1(t) + \lambda_{21}P_2(t) = -\left( \lambda + \frac{1}{t_{TO}} \right) P_1(t) + \frac{1}{t_{TO}} P_2(t), \\
\frac{dP_2(t)}{dt} &= \lambda_{12}P_1(t) - \lambda_{21}P_2(t) + \lambda_{32}P_3(t) = \frac{1}{t_{TO}} P_1(t) - \frac{1}{t_{TO}} P_2(t) + \frac{1 + \lambda t_{TO}}{\lambda t_{TO}^2} P_3(t), \\
\frac{dP_3(t)}{dt} &= \lambda_{13}P_1(t) - \lambda_{32}P_3(t) = \lambda P_1(t) - \frac{1 + \lambda t_{TO}}{\lambda t_{TO}^2} P_3(t)
\end{align*}
\]  

(8)

Due to the linear dependence of system (8) for solving one of the equations, we replace the normalizing condition: \( P_1(t) + P_2(t) + P_3(t) = 1 \), supplementing the system with the initial conditions: \( P_1(0) = 1, \ P_2(0) = P_3(0) = 0 \). The system will take the form:
\[
\begin{align*}
\frac{dP_1(t)}{dt} &= -\left(\lambda + \frac{1}{t_{TO}}\right)P_1(t) + \frac{1}{\tau_{TO}}P_2(t), \\
\frac{dP_2(t)}{dt} &= \frac{1}{t_{TO}}P_1(t) - \frac{1}{\tau_{TO}}P_2(t) + \frac{1+\lambda t_{TO}}{\lambda t_{TO}^2}P_3(t), \\
\frac{dP_3(t)}{dt} &= P_1(t) + P_2(t) + P_3(t) = 1
\end{align*}
\]

(9)

To solve the system of differential equations (9), we use the Laplace transformation. Let \( P_1(t) \) have an image \( \mathcal{L}\{P_1(t)\} = P_1(s) \) and, in accordance with the property of differentiation:

\[
\mathcal{L}\{\frac{dP_1(t)}{dt}\} = sP_1(s) - P_1(0)
\]

(10)

Applying the Laplace transformation to other probabilities, setting the initial conditions: \( t = 0 \), \( P_1(0) = 1 \), \( P_2(0) = P_3(0) = 0 \), taking into account the condition \( 1 \to \mathcal{L}\{P_1(t)\} = \frac{1}{s} \), we obtain next system:

\[
\begin{align*}
xP_1(x) - 1 + \left(\lambda + \frac{1}{t_{TO}}\right)P_1(x) - \frac{1}{\tau_{TO}}P_2(x) &= 0, \\
xP_2(x) - \frac{1}{t_{TO}}P_1(x) + \frac{1}{\tau_{TO}}P_2(x) - \frac{1+\lambda t_{TO}}{\lambda t_{TO}^2}P_3(x) &= 0, \\
P_1(x) + P_2(x) + P_3(x) - \frac{1}{x} &= 0.
\end{align*}
\]

(11)

Passing to transition intensities, we have:

\[
\begin{align*}
xP_1(x) - 1 + (\lambda_1 + \lambda_3)P_1(x) - \lambda_2P_2(x) &= 0, \\
xP_2(x) - \lambda_1P_1(x) + \lambda_2P_2(x) - \lambda_3P_3(x) &= 0, \\
P_1(x) + P_2(x) + P_3(x) - \frac{1}{x} &= 0.
\end{align*}
\]

(12)

The solution to the system of linear algebraic equations (12) has the form:

\[
P_1(x) = \frac{\lambda_{32}x + x^2 + \lambda_{21}x + \lambda_{32}\lambda_{21}}{x(\lambda_{32}x + \lambda_{32}\lambda_{12} + \lambda_{32}\lambda_{13} + x^2 + \lambda_{12}x + \lambda_{13}x + \lambda_{21}x + \lambda_{21}\lambda_{13} + \lambda_{32}\lambda_{21})},
\]

(13)

\[
P_2(x) = \frac{\lambda_{21}x + \lambda_{32}\lambda_{12} + \lambda_{32}\lambda_{13}}{x(\lambda_{32}x + \lambda_{32}\lambda_{12} + \lambda_{32}\lambda_{13} + x^2 + \lambda_{12}x + \lambda_{13}x + \lambda_{21}x + \lambda_{21}\lambda_{13} + \lambda_{32}\lambda_{21})},
\]

(14)

\[
P_3(x) = \frac{x + \lambda_{21}}{x(\lambda_{32}x + \lambda_{32}\lambda_{12} + \lambda_{32}\lambda_{13} + x^2 + \lambda_{12}x + \lambda_{13}x + \lambda_{21}x + \lambda_{21}\lambda_{13} + \lambda_{32}\lambda_{21})}.
\]

(15)
For the steady state of operation \( \frac{dP_1(t)}{dt} = \frac{dP_2(t)}{dt} = \frac{dP_3(t)}{dt} = 0 \), system (8) is transformed into a system of linear algebraic equations with the next form:

\[
\begin{align*}
\left\{ \begin{array}{l}
-(\lambda_{12} + \lambda_{13}) P_1 + \lambda_{21} P_2 &= \left( \frac{1}{T_{TO}} \right) P_1 + \frac{1}{\tau_{TO}} P_2(t) = 0, \\
\lambda_{12} P_1 - \lambda_{21} P_2 + \lambda_{32} P_3 &= \frac{1}{T_{TO}} P_1 - \frac{1}{T_{TO}} P_2 + \frac{1}{\tau_{TO}} P_3 = 0, \\
\lambda_{13} P_1(t) - \lambda_{32} P_3 &= \lambda P_1(t) - \frac{1}{T_{TO}} P_3 = 0.
\end{array} \right.
\]

Supplementing system (16) with the norming condition \( P_1 + P_2 + P_3 = 1 \), we obtain a solution for the final probabilities of states:

\[
\begin{align*}
P_1 &= \frac{T_{TO}}{\lambda^2 t_{TO}^2 \tau_{TO} + \tau_{TO} + 2\lambda t_{TO} \tau_{TO} + \lambda^2 t_{TO}^3 + t_{TO} + \lambda t_{TO}^2}, \\
P_2 &= \frac{T_{TO}}{\lambda^2 t_{TO}^2 \tau_{TO} + \tau_{TO} + 2\lambda t_{TO} \tau_{TO} + \lambda^2 t_{TO}^3 + t_{TO} + \lambda t_{TO}^2}, \\
P_3 &= \frac{\lambda t_{TO}^3}{\lambda^2 t_{TO}^2 \tau_{TO} + \tau_{TO} + 2\lambda t_{TO} \tau_{TO} + \lambda^2 t_{TO}^3 + t_{TO} + \lambda t_{TO}^2}.
\end{align*}
\]

3. Results and discussion
Consider an example of calculating the final probabilities carried out for a device for which a life of 10 years is declared. Table 5 shows the values of the final probability \( P_1 \) calculated by equations (14) - (16) for \( \tau_{TO} = 10 \).
Table 5. Probability of availability of the technical means.

| $t_{TO}$, years | $\lambda$, hour$^{-1}$ | 0.1  | 0.5  | 1    | 2    | 5    | 10   | The final probability |
|-----------------|------------------------|------|------|------|------|------|------|-----------------------|
| 10$^{-4}$       | 0.9358                 | 0.8826| 0.8797| 0.8797| 0.8797| 0.8797| 0.8797 |
| 10$^{-5}$       | 0.9958                 | 0.9958| 0.9958| 0.9958| 0.9958| 0.9958| 0.9958 |
| 10$^{-6}$       | 0.9977                 | 0.9977| 0.9977| 0.9977| 0.9977| 0.9977| 0.9977 |
| 10$^{-4}$       | 0.9232                 | 0.7728| 0.7228| 0.7093| 0.7086| 0.7086| 0.7086 |
| 10$^{-5}$       | 0.9938                 | 0.9918| 0.9918| 0.9918| 0.9918| 0.9918| 0.9918 |
| 10$^{-6}$       | 0.9988                 | 0.9988| 0.9988| 0.9988| 0.9988| 0.9988| 0.9988 |
| 10$^{-4}$       | 0.9187                 | 0.7020| 0.5724| 0.4914| 0.4734| 0.4724| 0.4724 |
| 10$^{-5}$       | 0.9920                 | 0.9785| 0.9747| 0.9739| 0.9739| 0.9739| 0.9739 |
| 10$^{-6}$       | 0.9991                 | 0.9991| 0.9991| 0.9991| 0.9991| 0.9991| 0.9991 |

Figure 5 shows graphs of the dependence object readiness state probability $P_1$ on the maintenance frequency $t_{TO}$, for various combinations of failure rates $\lambda$ and duration of maintenance $\tau_{TO}$.

The graphs show the presence of an extremum, which indicates that, for given values $\lambda$ and $\tau_{TO}$, there is an optimal frequency of maintenance and, accordingly, the maximum limit value of the probability of the state of readiness of an object [10].

Figure 6 shows graphs of the probability values of the state of an object in an inoperative state depending on the frequency of maintenance.
4. Conclusion

The obtained analytical solutions (17) - (18) for the steady-state operation mode provide an opportunity to solve reliability optimization problems (Figure 7).

Thus, modeling the reliability of technical systems is an important factor in the design and modernization of security systems located at transport infrastructure facilities, making it possible to formulate reasonable requirements for the technical means used, as well as to carry out their rational selection based on the tasks assigned to the security system.

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