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APPLICATION OF METHODS FOR DETERMINING THE RELIABILITY OF MICROPROCESSORS IN TRAFFIC CONTROL DEVICES

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Abstract – The article presents the issue of reliability of railway traffic control systems as a key element responsible for safety in transport tasks. It discusses factors affecting the reliability of devices used in traffic control systems and factors influencing the high level of safety and reliability of traffic control devices. The importance of reliability in microprocessor-based control systems is also discussed. As a final result, some methods for calculating the reliability of microprocessors and implementing them in traffic control devices are presented.

Keywords – automation, traffic signal systems, safety, reliability

INTRODUCTION

Every day, we are surrounded by electronics that we often do not even realize. At home, we use simple devices that help us in our daily activities, but as soon as we step outside, we enter a world of much more complex systems. They operate in the background and support us in every activity related to movement. We only see the end result - a traffic light, an information board, a railroad crossing - but what really makes them work is hidden inside. Microprocessors play a key role here, along with the entire electronic structure, which must function flawlessly regardless of the conditions. When we drive a car, we count on the traffic lights to change at the right moment and on the traffic management systems to coordinate traffic so that collisions do not occur. When we board a train, we trust that the railway traffic control devices will correctly detect the position of the train, set the switches, and ensure safe train operation. In power engineering and industrial automation, appropriate controllers monitor operating parameters and react faster than a human would be able to notice any change. In each of these cases, it is a microprocessor that makes decisions and responds to data from sensors. There is no margin for error in such systems. A single component failure is enough to disrupt the operation of the entire system. That is why it is said that a system is only as reliable as its weakest component. If the smallest part fails, it can lead to delays, false signals, traffic stoppages, or even serious incidents. To minimize this risk, engineers

use a set of methods to help predict the reliability of microprocessors. These methods allow them to assess whether a given system will cope under specific conditions, what the probability of its failure is, and how a potential fault will affect the operation of the whole system. In practice, this involves analyzing many factors. The system's resistance to temperature, humidity, overload, and electromagnetic interference is tested. Predictions are made about how the microprocessor might react to memory damage, incorrect input data, or abnormal signal patterns. Mathematical models, statistics, risk analysis, and simulation tests are used. The goal is for the system to function as intended for a specified period of time and to be able to respond to a fault in such a way that it does not lead to a dangerous situation. A well-designed reliability assessment method helps to determine whether a traffic control device is capable of performing all its functions without failure and whether it can cope even when some of its components start to malfunction. This is particularly important in transport, where the consequences of an error can be serious. That is why railway, road, and air traffic control systems are designed to be resistant to single failures and have appropriate safeguards. Microprocessors used in such devices must meet the highest standards and be tested under various conditions before they are put into actual use. Modern traffic control systems are developing very rapidly. There is more automation, intelligent algorithms, and communication between devices. Microprocessors have increasing computing power, but at the same time, they must work reliably in an environment full of interference. In such conditions, appropriate reliability assessment methods become not only a tool to support design, but also the basis for creating safe systems. This is why the topic of applying methods for determining the reliability of microprocessors in traffic control devices is so important. It allows us to understand how systems that must operate continuously are designed, how their weak points are predicted, and how user safety is ensured. This knowledge is crucial both from the point of view of an engineer and anyone who uses transport infrastructure, even if only on their way to work.

COMPONENTS OF TRAFFIC CONTROL SYSTEMS

Traffic control systems include a range of components and technologies that work together to ensure smooth, safe, and efficient transportation. The basic elements of such systems include:

- Sensors and measuring devices – monitor traffic and collect data on the status of the system.
- Control software – analyzes data and issues appropriate commands to manage traffic.
- Actuators – executive devices that perform actions in accordance with system commands.
- Communication interfaces – ensure the exchange of information between system components and external users (e.g., traffic controllers).

Based on this, it is worth noting that the reliability of traffic control systems is the result of proper design, implementation, operation, and maintenance of devices, as well as proper integration into a whole that allows for correct operation. However, one must not forget about all the elements that directly make up the traffic control systems, being their key components, while at the same time being the leading components influencing the correct operation of the systems and their reliability. These include:

- Equipment: components such as sensors, actuators, servomechanisms, actuators, as well as

the infrastructure itself (e.g., traffic lights, road control devices). The reliability of the equipment depends on its quality, durability, appropriate selection, and operating conditions.

- Software: traffic control algorithms that process input data from sensors, convert it into appropriate control signals, and manage the logic of the system. Programs must be designed to minimize the risk of errors that could lead to failure.
- Power supply and connectivity: traffic control systems must be designed to ensure continuity of operation even in the event of a power failure. Backup power supplies, redundant power sources, and stable communication infrastructure (e.g., wireless connectivity, wired networks) are essential.
- Redundancy and safety algorithms: Redundancy in traffic control systems is a process in which backup components and mechanisms are introduced to take over functions in the event of a failure of the main system components. Examples include hardware redundancy (e.g., two independent servers) and redundancy in control algorithms that monitor the system and respond to errors.

THE IMPORTANCE OF RELIABILITY IN THE CONSTRUCTION OF TRAFFIC CONTROL SYSTEMS

The reliability of traffic control systems is a key element in ensuring the safety, efficiency, and smooth flow of transport, whether by road, rail, air, or water. There are several different reasons why reliability and ongoing research into reliability have such a significant impact, including:

1. System safety – traffic control systems are responsible for preventing traffic accidents that may occur in everyday traffic and transport tasks. Any possible failure can pose a threat to user safety, which is why reliability in safety analysis means eliminating all possible traffic hazards that could also lead to a threat to human life and health.
2. Traffic management – as in point number one, it is worth noting that proper traffic management ensures safety and is an essential element for efficient traffic management. Ensuring a high level of traffic flow and, at the same time, the most optimal one. The level of reliability affects the correct operation of information signaling or the system for monitoring traffic events, whereby a reliable system allows for smooth traffic management, eliminating any bottlenecks that may occur in traffic incidents.
3. Energy efficiency – for all possible modes of transport where we can talk about transport systems, i.e., the movement of vehicles, trains, planes, or ships. Traffic control is automatic, so the reliability of the equipment has a direct impact on energy efficiency. Malfunctioning traffic control systems, i.e., possible faults, can result in suboptimal energy or fuel consumption due to the possibility of bottlenecks, i.e., the stopping of means of transport and possible rapid starts to resume transport operations.
4. Transport cost optimization – a traffic control system failure leads to costly repairs and downtime, which can affect transport operations. In addition, traffic problems can generate additional costs related to delays, fuel consumption, and additional waiting time.
5. Transport efficiency – traffic control systems are largely used for tasks carried out in public transport, and in this regard, the reliability of control systems, such as train or subway traffic management, allows for the correct execution of transport activities according to the

established schedule, which directly affects punctuality. A system failure can lead to delays that affect the entire transport network, reducing passenger comfort and system efficiency.

6. Crisis management – in the event of natural disasters, technical failures, or emergency situations, reliable traffic control systems are essential for a quick and effective response. Proper control can enable faster evacuation of people, ensure access for emergency services, or minimize the effects of a failure.
7. Increasing capacity in transport infrastructure – traffic control systems enable better use of existing transport infrastructure. With proper traffic management, the capacity of roads, railways, and airspace can be increased, which is particularly important in the face of growing transport volumes.
8. Compliance with applicable regulations – modern traffic control systems must meet specific technical and operational standards and regulations. Reliability is one of the main requirements for systems to operate in accordance with the law and meet environmental standards.

As indicated above, traffic control systems are responsible for ensuring the smooth flow and safety of traffic in various contexts, which is why they are so important, as they are a key element in every branch of transport and energy transmission. The following areas can be identified where the reliability of traffic control systems is fundamental to their functioning:

- Road transport: traffic control systems such as traffic lights, urban traffic management systems, traffic monitoring systems, and remote management systems.
- Railway: train control systems, including automatic traffic control systems that prevent collisions and ensure the safe movement of vehicles.
- Energy: control systems in power plants and power grids, where monitoring and managing the flow of raw materials, energy, and equipment is crucial for continuity of supply.
- Industry: traffic control systems in industrial process automation, such as production lines, robotics, and material flow management.

FACTORS AFFECTING THE RELIABILITY OF MOTION CONTROL SYSTEMS

The reliability of traffic control systems in every branch of transport - rail, road, sea, and air - is the result of the synergy of many technical, programming, and operational factors. According to the definition of reliability and dependability presented by Avizienis, Laprie, and Randell [2, 14], a properly designed system should not only function correctly, but also maintain functionality despite potential component failures, environmental errors, or disturbances. This is particularly important in transportation systems, as their potential failures lead directly to the risk of loss of life and enormous economic losses. Reliability is primarily influenced by four key groups of elements: hardware, software, power supply and connectivity, and redundancy and security algorithms.

Hardware as the foundation of reliability

In every branch of transport, equipment is the physical basis for the functioning of the traffic control system. This includes both infrastructure components and electronic devices that acquire, process, and execute control commands.

- Rail transport

  In rail transport, equipment is critical. It includes, among other things:
  - track sensors, including track circuits, axle counters, and radars,
  - light signals,
  - points and their drives,
  - computers and SRK systems,
  - local and central controllers,
  - servo mechanisms and actuators.

As demonstrated by the operational studies of Dyduch and Kornaszewski [4], the correct operation of these devices reflects the actual failure rate of the entire railway traffic system, as even a single failure can lead to route blocking or incorrect information about track occupancy. RAMS standards, such as EN 50126 (IEC 62278) [9], define detailed requirements for durability, environmental conditions, vibration resistance, humidity, temperature, and electromagnetic interference. Equipment must be designed to meet the required safety levels (SIL) in accordance with IEC 61508 [8]. This is also consistently confirmed by operational practice, including the predictive models presented by Kornaszewski and Pniewski [11, 13], who emphasize the need to predict the service life of railway equipment based on operational data and simulations.

- Road transport

In road systems, equipment includes traffic lights, loop detectors, radar detectors, traffic controllers, and network infrastructure. As in railway systems, resistance to environmental conditions and the quality of components directly affect failure rates.

- Maritime and air transport

In maritime systems, hardware components include radars, AIS systems, transmitters, receivers, and on-board automation systems. In aviation, these include radio beacons, radars, ILS devices, transponders, and air traffic control servomechanisms. Girtler [7] points out that in maritime systems, equipment reliability can be modeled stochastically, which is also confirmed by the approach used in aviation.

System software as the key to correct information processing

Modern traffic control systems are largely computer-based, and their reliability depends as much on the quality of the software as on the quality of the hardware.

According to Musa [18] and Modarres [17], software reliability consists of minimizing design errors, proper testing, verification, and validation of functions, and adapting algorithms to the hardware and operating environment. This is particularly important in transportation - a faulty algorithm can lead to incorrect control decisions, even if the hardware is working properly.

- Software in railway systems

  Systems such as:
  - Ebilock,
  - ESTW,

- computer-based signal box systems,

must meet the highest safety requirements (SIL4). The software is responsible for, among other things:

- input signal analysis (e.g., track occupancy information),
- traffic control logic management,
- detecting irregularities,
- generating control commands.

According to Zio [29] and Zeigler [28], these systems are modeled using advanced simulation methods, including Monte Carlo, to assess the probabilities of errors and ensure appropriate response procedures. In road, sea, and air transport, software performs similar functions, but in rail transport, the specific nature of the closed infrastructure and the consequences of collisions mean that safety requirements are particularly stringent.

Power supply and communication as a condition for continuity of operation

Continuity of power supply and communication is one of the fundamental elements of ensuring the reliability of a traffic control system. According to IEC 61508 [8], every safety-critical function must have safeguards to prevent loss of functionality.
In railway systems, the following forms of power continuity are used to ensure the highest possible level of safety:

- two independent power supply circuits (primary + backup),
- UPS emergency power supply,
- batteries and power generators,
- high-availability telecommunications networks,
- redundant connections (fiber optic + radio link).

Authorized operational tests (Dyduch, Kornaszewski [4]) confirm that loss of communication or power supply is one of the main causes of SRK device malfunction – hence it is crucial to design systems that are resistant to interference and have a multi-level power supply.

Backup power supplies are used in traffic signaling, but their level is not as high as in railways due to the lower criticality of threats. Nevertheless, a prolonged power outage can lead to traffic chaos.

In aviation, the continuity of power supply to radars and navigation equipment is critical. These systems are duplicated multiple times (so-called hot standby), and failures are resolved in real time. Similar solutions are used in maritime navigation systems.

Redundancy and security algorithms

Redundancy covers both hardware and algorithmic elements, in accordance with the concept described by Koren and Krishna [10] and Siewiorka and Swarz [26]. Its purpose is to enable the system to continue operating in the event of damage to one of its components.

- Hardware redundancy
  - multiple independent communication channels,

  - duplicate computers and controllers,
  - backup input/output modules,
  - automatic switching without operator intervention.
- Software and algorithmic redundancy
  - algorithms monitoring the correctness of input data,
  - models verifying the consistency of information (e.g., whether the track occupancy signal is consistent with other data),
  - fail-safe procedures, in which the system switches to a safe state in case of any uncertainty.

This is of great importance in railways – every SRK system is designed according to the philosophy of positive safety, which means that in case of ambiguity, the system switches to a traffic stop state.

Probabilistic methods described by Ross [25] or Bertsekas and Tsitsiklis [3], as well as Markov models used in SRK reliability analyses (Podgórska [24]), allow for a mathematical assessment of the effectiveness of redundancy and the probability of critical failures.

METHODS FOR TESTING THE RELIABILITY OF TRAFFIC CONTROL SYSTEMS

Using mathematical methods, we can determine the probability of events occurring, including equipment failure, through estimated probability calculations. This is one of the most basic methods of estimating the probability of failure.

One such method that helps determine probability and predict failures is the Markov process. It is a study based on a sequence of events in which the probability of each event is determined solely on the basis of the result of the previous one. Analyzing this process mathematically, we can see that it is a stochastic process that satisfies the Markov property, which means that the probability distribution of future states of the process is derived from and determined solely by its current state, regardless of the past. In research on the reliability of traffic control systems, mathematical methods that allow the probability of equipment failure to be estimated play an important role. The use of probability calculus makes it possible to predict failures and plan maintenance activities based on statistical analysis of operational data [2, 3, 4]. One of the methods used to model failure processes is the Markov process, which is based on the analysis of a sequence of events in which the future state of the system depends solely on its current state, regardless of the past [24, 25].

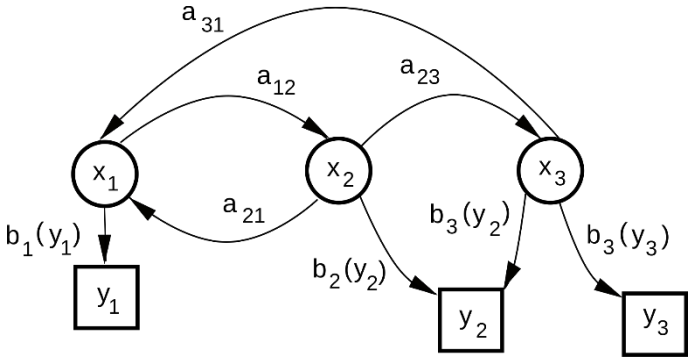

Figure 1. Example of Markov Process [8]

Markov models can be represented in the form of equations or state diagrams. In graphical form, states are represented as circles, and transitions between them are represented by arrows indicating possible changes [8]. The main features of a Markov process include the Markov property, a finite or infinite number of states, the possibility of determining a transition matrix, and a stationary distribution in the case of ergodic processes [24]. Depending on the time classification adopted, Markov processes can be discrete or continuous. An example is a two-state process, where the transition from one state to another is described by a transition matrix [25].

– Markov property: the probability of moving to the next state depends only on the current state, not on previous states. Formally, it looks as follows:

$$\boldsymbol{P}(\boldsymbol{X_n} = \boldsymbol{x_{n-1}} | \boldsymbol{X_n} = \boldsymbol{x_n}, \boldsymbol{X_{n-1}} = \boldsymbol{x_{n-1}}, \dots, \boldsymbol{X_0} = \boldsymbol{x_0}) = \boldsymbol{P}(\boldsymbol{X_{n+1}} = \boldsymbol{x_{n+1}} | \boldsymbol{X_n} = \boldsymbol{x_n} \quad (1)$$

Model No. 1

where:

X_n - represents the state of the process at time *n,*
X_{n+1} - the state of the process at the next time step *n+1*,
x_n and $x_{(n+)(1)}$ - are specific values (states) that can be assumed by X_n and X_{n+1}

The Markov property defined by formula (1) is an element of the Markov chain, which is defined by stochastic processes. It specifies that the future of the system depends solely on its state X_n, and not on the states preceding the indicated property, from which we can conclude that past states will not affect the future states of the system, provided that we know its current state. Therefore, formula (1) is the basis for analyzing and modeling phenomena that can be described as Markov chains. In the context of traffic control device reliability, Markov processes allow for the modeling of component failures and the prediction of when they will occur. This approach enables the development of maintenance schedules and the optimization of spare parts inventory, which increases system availability

[5, 6, 11, 22, 23]. In addition, simulation methods, including computer simulations based on Markov chains, allow for the analysis of traffic control system behavior in emergency conditions [29]. Thanks to simplification (dependence on the current state instead of the entire history), it enables effective forecasting and simulation in various fields. These states can be classified according to the following properties:

- States: A Markov process can have a finite or infinite number of states. In the case of a finite number of states, we are dealing with a Markov process on a discrete space; in the case of an infinite number of states, we speak of a of a continuous Markov process.
- Transition matrix: If we have a finite number of states, a Markov process can be described by a transition matrix P, where the element P_{ij} determines the probability of transition from state *i* to state *j*.
- Stationary distribution: If the Markov process is ergodic (that is, it satisfies certain conditions), then in the long run the system reaches the so-called stationary distribution, which does not change with time. Then the probability of finding the system in a given state remains constant.
- Time: Markov processes can be classified based on time:
    - Discrete time: states change in units of time, such as after each unit.
    - Continuous time: state changes can occur at any time.

The simplest example is a Markov process with two states (e.g., state A and state B):

- The transition from A to B has probability p.
- The transition from B to A has probability q.

From which it follows that the transition matrix would then look as follows:

$$\mathrm{P} = \begin{matrix} 1-\mathrm{p} & \mathrm{p} \\ \mathrm{q} & 1-\mathrm{q} \end{matrix} \tag{2}$$

Model No. 2 (matrix)

The Markov process in terms of control device reliability can play an important role in modeling various aspects of the control device manufacturing process and selecting the appropriate microprocessors and components, which will ultimately work together to form a motion control system. It also makes it possible to predict the failure of individual components, thus enabling the application of service guidelines that allow for timely maintenance or service activities to ensure the continuity of system use. Thanks to the ability to predict failures, it also allows for the maintenance of an optimal level of spare parts that may need to be replaced. Overall, this significantly improves the decision-making process in companies that supply traffic control systems. Another approach is parametric models of system lifetime, which allow the prediction of failures of individual components. Among the most commonly used models are the exponential model, the Weibull model, and extreme value models [17, 27]. The exponential model describes phenomena in which the rate of change is proportional to the current value and is used, among other things, to model cooling processes or the decline in component reliability [16, 17, 19, 21]. The Weibull model, thanks to the flexibility of scale and shape parameters, allows for more accurate prediction of device lifetime and analysis of failure risk under various operating conditions [17, 27]. The Weibull distribution density function allows for statistical modeling of failure

processes and the creation of operational scenarios in control systems engineering [18, 20].

- In addition to the methods mentioned above, reliability analysis also uses normative guidelines such as IEC 61508 and IEC 62278 (EN 50126), which define standards for the design of safety-critical electrical and electronic systems [8, 9]. Engineering practice also takes into account computer simulations and Monte Carlo modeling, which allow the behavior of systems to be predicted under extreme conditions and service decisions to be optimized [29].
- By combining analytical, probabilistic, and simulation methods, it is possible to create comprehensive reliability models for traffic control systems. This allows for effective operational planning, minimization of failure risk, and ensuring system continuity, which is crucial for maintaining rail and road transport safety [4, 5, 11, 23].

We can distinguish several parametric models that can be used very successfully as basic models for determining the lifetime of a stationary system and, at the same time, as models for determining the time of possible failures, which are specified for each of the components and mechanisms where a failure may occur. They can use probabilistic analyses based on the laws of physics to determine failure modes, which then allow us to select the appropriate model for analysis. In the study of microprocessors, we can use models such as the following to determine reliability:

- Exponential,
- Weibull,
- Extreme value.

An exponential model is a type of mathematical model that describes processes in which a change in quantity occurs in proportion to its current value. This means that the rate of increase or decrease depends on the quantity itself, leading to an exponential increase or decrease in that quantity over time. The general formula (3) for this model is:

$$y(t) = y_0 e^{kt} \tag{3}$$

where:
y(t) - is the value of the function at time t,
y_0 - is the initial value at time t=0
k - is the constant rate of increase or decrease (if k>0, the model describes an increase, and if k<0, a decrease),
t - is time,
e - is the base of the natural logarithm (approx. 2.718).

Formula (3) describes an exponential process that can be used to model many natural, technical, and social phenomena. When used in the field of technology and computer science, it allows for the process of determining data based on its increasing generation. It also allows for the application of the appropriate cooling process for objects using Newton's law of cooling, which states that the temperature differences between objects and their surroundings change exponentially over time. Therefore, the aforementioned formula (3) is the basic mathematical model for many phenomena

in which changes are proportional to the current state. It is used to model both growth and decay, and its applications cover a wide range of sciences, including natural sciences, technical sciences, and social sciences.

Another of these models is the Weibull model, where the probability distribution is widely used in reliability analysis, risk assessment, failure analysis, and life time modeling. It is a continuous distribution that can describe both processes with exponential characteristics (constant failure time) and processes with varying failure rates over time (e.g., increasing or decreasing failure intensity). The probability density function in the Weibull model can be defined by the following formula (4):

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x|\lambda)^k} & dla\ x \geq 0 \\ 0 & dla\ x < 0 \end{cases} \quad (4)$$

where:
x - is a random variable (e.g., time to failure),
λ>0 - is the scale parameter that controls the width of the distribution,
k>0 - is the shape parameter that affects the shape of the distribution.

The Weibull method is also one of the methods that are part of the mathematical section of extreme values. By using this method, it is possible to predict the service life of devices with microprocessors for the application of extreme parameters during use, which allows for determination.

However, it is worth noting that there are also many other methods developed to determine the reliability of devices. Their suitability depends on factors resulting from their real-time operation and the extreme parameters to which they are exposed. The reliability coefficients used measure the frequency of failures in relation to the total operating time of the system, which allows for proper maintenance of devices and the selection of more precise models to support the testing of device reliability in the future. In addition, through the use of computer simulations, it is possible to predict behavior under various operating conditions of the devices, and it is also possible to simulate the behavior of traffic control systems in terms of operation in the event of a failure. The situation of simulation in this form allows the behavior of the system during a failure to be determined, making it possible to apply measures to improve or ensure continuity of movement in the event of specific failures. Using formula (4), which is a probability density function of the Weibull distribution, it is possible to perform statistical predictions and modeling of phenomena in engineering, which makes it possible to use it in reliability analysis, where it allows the creation of a model determining the lifetime of a device based on the failure rate of computers, IT systems, and networks. The Weibull distribution is a very flexible model that can be adapted to different data shapes thanks to the parameters λ (scale) and k (shape). Its applications include reliability analysis, bioinformatics, meteorology, economics, and many other fields where modeling the variability of phenomena over time is important.

SUMMARY

Assessing the reliability of microprocessors in railway traffic control devices has become one of the main areas of research in transport, as these small circuits determine the safety of the entire system. Today's railways are heavily dependent on electronics, algorithms, and precisely developed logical relationships. Microprocessors not only execute commands, but also control the relationships between signals, monitor the status of devices, and supervise the operation of actuators. In practice, they are responsible for decisions on which people's lives depend. That is why so much emphasis is placed on analyzing their reliability and on methods for predicting their behavior. Over the years, the focus has shifted from electronics alone to the entire process chain: from design and operation to maintenance. The first systematic operational studies showed that data from real-world device operation is crucial. In a laboratory environment, everything works stably, but in the field, there are temperature fluctuations, humidity, electromagnetic interference, and natural aging processes. The first publications documenting the behavior of level crossing signals already indicated that actual faults deviate from theoretical assumptions [1]. This changed the approach to failure prediction and initiated a trend towards building models based on operational observations. In the following years, research on microprocessor devices expanded to include system analysis. It was noticed that a single microprocessor module can work perfectly, but if it works with lower-quality devices or is operated incorrectly, the entire system loses some of its reliability. Therefore, not only the equipment was analyzed, but also the processes, documentation, employee training methods, and human-machine interactions. Work on anthropotechnics in traffic control [3] showed how much human factors affect overall safety. Operators work under pressure, in changing conditions, often based on routine. A microprocessor may be reliable, but human decisions regarding intervention or resetting devices are equally important. At the same time, modeling and simulation techniques were developing. Discrete and system models, previously used mainly in computer science and automation, became the basis for building complete test environments. Zeigler's theory [11] made it possible to create models that map the behavior of microprocessor devices in simulated operating cycles, introducing the possibility of analyzing extreme scenarios without risk to real infrastructure. This makes it possible to evaluate the response of devices to non-standard error sequences, signal interference, overloads, or power failures. The next step was the development of predictive methods that allow us to predict when a device will begin to show signs of degradation. Simulation models coupled with operational data began to be used to estimate parameters such as service life, signal quality, operational stability, and failure frequency [4]. This approach proved particularly useful because it enabled maintenance planning in a way that minimizes the risk of unplanned downtime. Instead of waiting for a device to fail, it is possible to predict when its parameters will begin to deviate from the norm. This, in turn, helps to optimize costs, which has been widely discussed in studies on the global costs of operating automation [1, 15]. Once it was understood that microprocessor systems require both ongoing diagnostics and probabilistic modeling, the natural step was to introduce mathematical methods based on Markov chains [8]. This method perfectly describes transitions between technical states. A microprocessor does not suddenly go from full

efficiency to failure; there are usually intermediate stages associated with signal degradation, non-random errors, or occasional restarts. Markov models allow these changes to be described numerically and show how often a device transitions between stable and unstable states. These approaches were previously used in the analysis of complex machines and technical objects [19], and after adaptation, they proved to be very effective in the railway sector. At the same time, research related to maintenance optimization has been developing. Models developed in recent years [6] show how to balance the frequency of inspections, repair costs, and the risk of failure. This is very important because microprocessors cannot be replaced too often – each intervention requires testing, certification, and interruptions in the operation of the equipment. The development of optimization models allows activities to be planned in such a way that they are economically justified, but at the same time do not adversely affect safety. It is worth noting that research into microprocessor reliability developed in parallel with trends observed in industry. In automotive manufacturing and logistics, great emphasis was placed on standardization, process mapping, and the elimination of uncertainty [12, 13]. The concepts of lean, traceability, real-time quality control, and component life cycle management also influenced the railway industry, where similar mechanisms were adapted to monitor traffic control devices. All these activities lead to one important conclusion. The reliability of microprocessors is not the result of a single factor, but a combination of many areas: design quality, implementation method, operational supervision, diagnostic data quality, mathematical methods, operator experience, and maintenance procedure quality. A traffic control system is an organism in which everything must work coherently and predictably. The microprocessor is the heart of this organism, but proper functioning requires the cooperation of the entire system. Today's research and practical experience show that an interdisciplinary approach is key. Technology, people, economics, and work organization are equally important. When these areas are successfully combined, a system is created that can not only be maintained, but also continuously developed and predicted in terms of its future behavior. Today's research is moving toward full data integration, automation of diagnostics, and the creation of dynamic predictive models. The future of microprocessor-based motion control systems lies in real-time analytics, machine learning, digital twins, and increasingly advanced methods of cost and safety optimization. However, the most important thing remains that the ultimate goal is human safety, and the reliability of microprocessors is one of the most important elements of this system.

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