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Reliability Assessment and Structural Design of a Microprocessor-Based Semi-Automatic Block System for Railway Transport

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Abstract

This paper presents the structural design and reliability assessment of a microprocessor-based semi-automatic block (MPAB) system for railway transport. The proposed system incorporates redundant control and power-supply channels, as well as wired and optical communication links between stations. A train dispatching algorithm is developed to verify interstation consent, track-section clearance, and equipment status before permitting train departure. System reliability is evaluated using a Markov-state model and component failure-rate data. The calculated mean time to first failure is 36,272 hours, compared with 12,987 hours for the conventional relay-based system. The results indicate that structural redundancy and microprocessor-based control can improve the reliability of railway blocking systems.

Keywords

Microprocessor-Based Semi-Automatic Block System, Railway Automation, Train Traffic Safety, Reliability Assessment, Markov Model

1. Introduction

Railway signalling, centralization, and blocking systems play an important role in ensuring train traffic safety and the continuous operation of railway infrastructure. The reliable functioning of these systems is essential for preventing unsafe train movements, maintaining the required separation between trains, and improving the efficiency of railway transportation. Therefore, increasing the reliability and operational performance of railway automation and telemechanics equipment remains an important engineering challenge [1].

Conventional relay-based semi-automatic block systems use electromechanical

components to control train movements between adjacent stations. However, the large number of relay elements and associated electrical circuits can complicate equipment maintenance, fault detection, and technical diagnostics. The application of microprocessor-based technologies provides opportunities to improve control logic, monitor equipment states, record operational events, and implement redundant system architectures [2].

A microprocessor-based semi-automatic block (MPAB) system must ensure that a departure signal is opened only when all required safety conditions are satisfied. These conditions include receiving valid consent from the adjacent station, confirming that the track section is clear, verifying the operational status of control equipment, and checking the consistency of axle-counter data. Reliable communication between stations is also essential for coordinating train departure, arrival confirmation, and track-section release.

In addition to the development of control algorithms, quantitative reliability assessment is necessary to determine the effectiveness of the proposed system architecture. Reliability indicators depend on component failure rates, the arrangement of redundant channels, and the presence of common elements whose failure may interrupt the operation of the entire system. Markov modelling provides a mathematical approach for representing transitions between operational, degraded, and failed states and for evaluating the probability of failure-free operation over a specified period [3].

2. System Design and Operating Algorithm

2.1. Train Departure Algorithm and Safety Interlocks

The train departure algorithm of the proposed microprocessor-based semi-automatic block (MPAB) system is implemented by the central processor unit at station A. Its primary function is to authorize train departure toward station B only when the required interstation blocking conditions, track-section clearance conditions, and equipment-status checks have been satisfied. The algorithm integrates the processing of digital messages exchanged between adjacent stations, axle-counting information, and the states of the relevant interlocking circuits.

As illustrated in **Figure 1**, the algorithm begins with the initialization of the internal variables and the acquisition of input data from the input/output modules, axle-counting equipment, communication modules, and interlocking relay circuits. The controller first verifies the operational status of the central processor and input/output modules. If a fault is detected in these components, the system indicates a malfunction and prohibits departure authorization.

The next stage involves checking the availability of the interstation communication channels. If the primary communication channel is unavailable, the controller attempts to switch to the standby channel. If neither channel can provide valid communication, the system indicates a communication fault and maintains the restrictive state. Thus, the departure procedure cannot proceed without the communication functions required for safe coordination between stations.

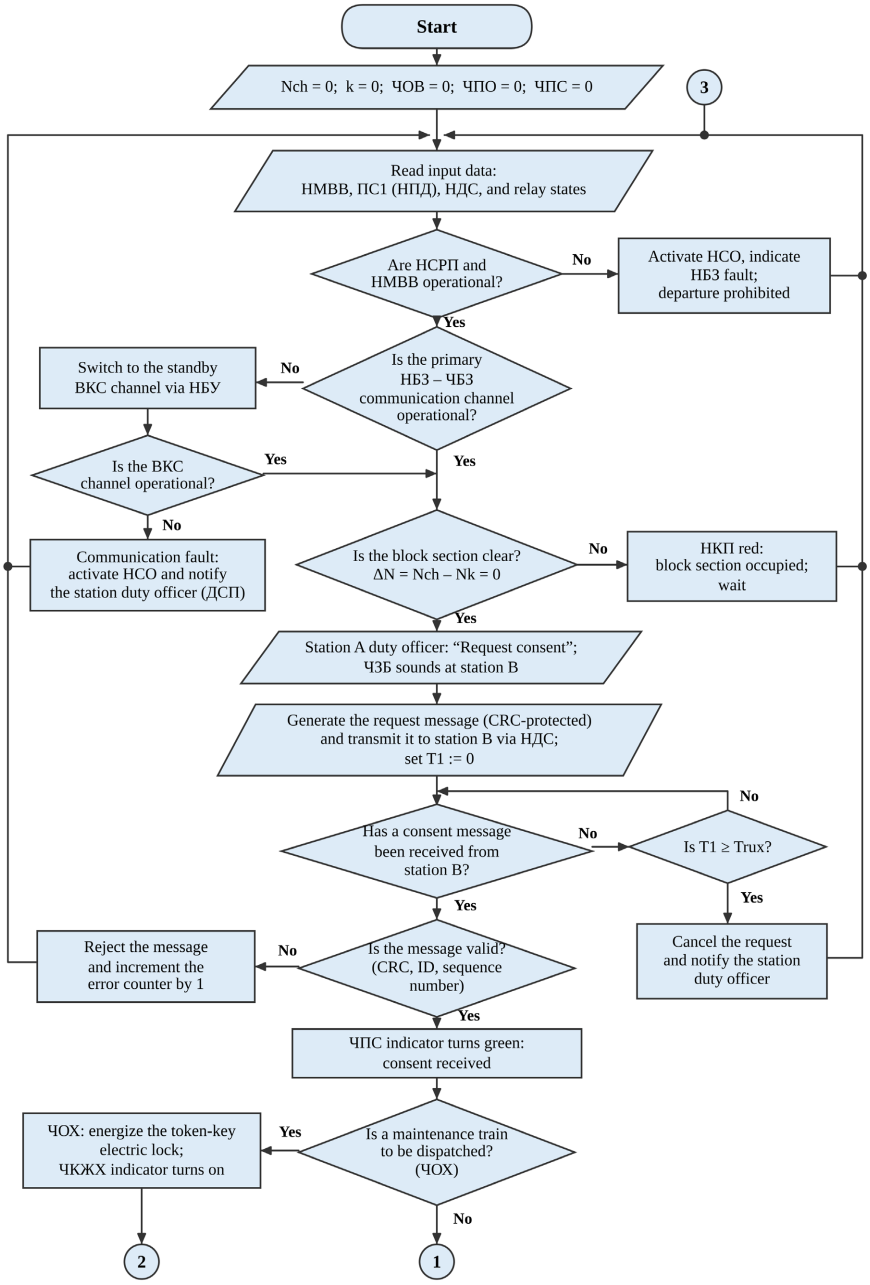


Figure 1. Train departure algorithm from station A to station B.

Before requesting consent from station B, the controller checks whether the block section is clear. The clearance condition is evaluated by comparing the axle counts recorded at the departure and arrival boundaries of the block section:

$$\Delta N = N_{\text{ch}} - N_{\text{k}} \tag{1}$$

where N_{ch} is the number of axles recorded by the counting point at the departure boundary at station A, and N_{k} is the number of axles recorded by the counting point at the arrival boundary at station B. According to the proposed algorithm, the block section can be considered clear when $\Delta N = 0$, provided that the other required occupancy and interlocking conditions are also satisfied. If the clearance

condition is not fulfilled, the block section remains indicated as occupied and the departure procedure is suspended.

After the preliminary checks have been completed, the station duty officer at station A initiates a request for consent from station B through the operator interface. The controller forms a digital request message protected by a cyclic redundancy check (CRC) and transmits it to the adjacent station. A response timer is started when the request is sent. If a valid consent message is not received within the configured timeout interval, the request is cancelled, a communication-related notification is generated, and departure authorization remains inhibited.

When a response arrives from station B, the controller verifies the integrity of the message using the CRC and checks its destination address and sequence number. Only a valid response is accepted as interstation consent. An invalid or inconsistent message is rejected, and the algorithm returns to the appropriate request or fault-handling stage without authorizing train departure.

Following the acceptance of interstation consent, the controller evaluates the departure-signal conditions. These include the availability of valid consent from station B, the absence of a preceding train in the block section, the required clear states of the station, approach, and switch-related track sections, the appropriate state of the token-key interlocking circuit where applicable, the operational status of the relevant control equipment, and the availability of a valid communication channel.

If all required conditions are satisfied, the controller energizes the departure-signal relay and monitors the resulting signal state through feedback. If the signal does not open as expected, the system indicates a signal-control fault and prevents the algorithm from proceeding under the assumption that departure has been authorized. When the first axle of the departing train is detected at the departure counting point, the departure signal is automatically closed and the block section is marked as occupied.

The controller continues to register the passing axles until the train has completely passed the departure counting point. It then transmits a train-departure message containing the recorded axle count to station B. If the acknowledgement is not received, the message is retransmitted according to the configured communication procedure. The departure information is subsequently used in the arrival-confirmation and block-section-release process.

After station B reports the arrival of the train, the controller compares the departure and arrival axle counts. If the counts agree and all applicable release conditions are satisfied, the block section may be released in accordance with the established operating procedure. If the counts disagree, the block section remains occupied. In the algorithm described in the system design, release following an axle-count discrepancy requires the designated recovery confirmation from station B rather than automatic release based solely on the passage of time.

The algorithm also provides a separate branch for handling a token-key operation associated with a maintenance or service train. In this case, the relevant interlocking conditions must be satisfied, and the block section remains occupied

until the token-key procedure has been completed in accordance with the applicable operating rules.

2.2. Development of the Structural Diagram of the Microprocessor-Based Semi-Automatic Block System

In railway transport, the operating algorithm of the control systems applied on line sections between stations is of primary importance for ensuring safe and uninterrupted train traffic. Replacing conventional relay-based semi-automatic block systems with microprocessor-based control systems makes it possible to improve the reliability, response speed, and diagnostic capabilities of the equipment [2] [4].

In the MPAB system, train traffic is controlled in two main modes: train departure and train reception [5]. The structural diagram of the MPAB system is shown in Figure 2.

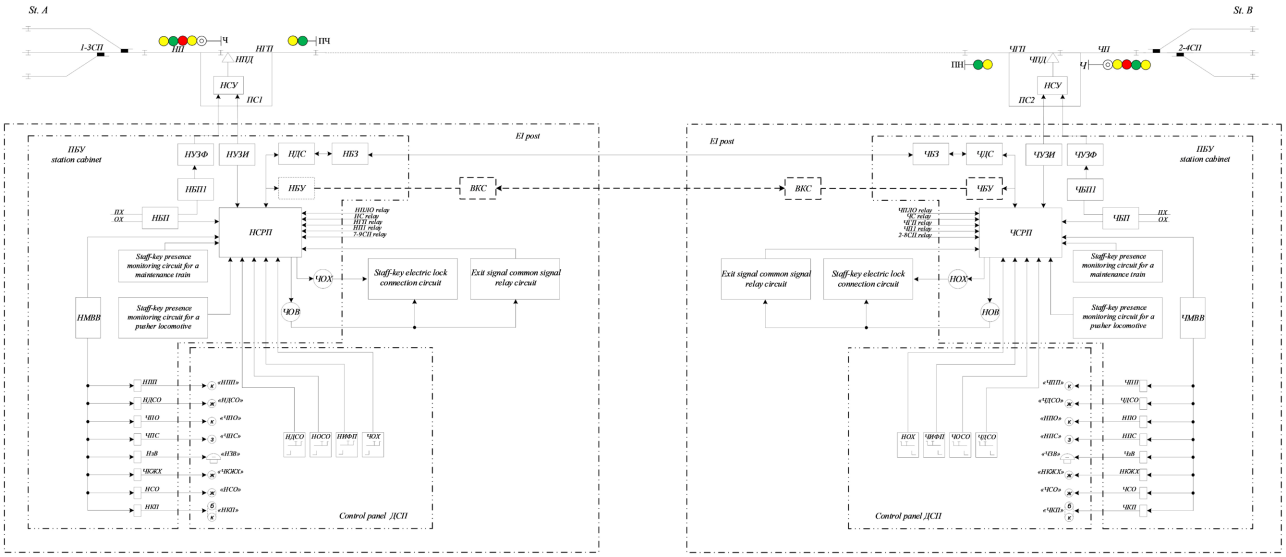


Figure 2. Structural diagram of the MPAB system.

As can be seen from the diagram, the MPAB system consists of two half-sets arranged symmetrically at stations A and B, which bound the line section. Each half-set comprises the station control cabinet (ПБУ) located at the electrical interlocking (EI) post, the control panel of the station duty officer (ДСП), and the axle-counting points (ПС1, ПС2) installed at the boundaries of the line section. The main units are designated by the index “N” at station A and “Ch” at station B, whereas the control-panel elements are designated according to the direction of train movement: “Ch” denotes the even direction (A → B) and “N” denotes the odd direction (B → A).

3. Reliability Assessment of the Microprocessor-Based Semi-Automatic Block System

Reliability is the property of a system to provide continuous and safe control of

train traffic under specified operating modes and specified conditions of maintenance and repair [3].

The calculation of quantitative reliability indicators of railway signalling, centralization and blocking (SCB) systems and devices is a recurring task in both their manufacture and operation [6] [7]. This task is addressed at various stages of the system life cycle.

The reliability indicators of a system are determined from the reliability indicators of its constituent elements, while the calculation method depends on the type of system. The reliability of railway automation and telemechanics (RAT) systems is characterized by the following properties (**Figure 3**).

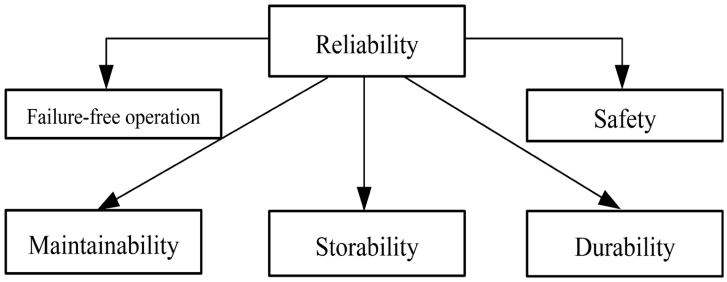


Figure 3. Reliability properties of RAT systems.

$Q(t)$ is the cumulative distribution function of the time to failure and is referred to as the probability of failure. Thus, $Q(t)$ is the probability that the time to failure is less than t, *i.e.*, the probability that the object fails within the time t. The main indicator of failure-free operation is the probability of failure-free operation $P(t)$, *i.e.*, the probability that the object operates without failure during a given operating time t:

$$P(t)+Q(t)=1 \tag{2}$$

The function $P(t)$ has the following properties:

- $P(0) = 1$ – the device is operable at the initial moment;
- $P(t) \to 0$ as $t \to \infty$ – the object cannot maintain its operable state for an unlimited time;
- $0 \le P(t) \le 1$ – the value of $P(t)$ lies between 0 and 1;
- $\mathrm{d}P(t)/\mathrm{d}t \le 0$ – the function is non-increasing, *i.e.*, reliability decreases over time.

The occurrence of a fault in an object is a random event, *i.e.*, it may or may not occur within a given time interval. Therefore, reliability theory is based on probability theory [3]. The failure rate $\lambda(t)$ is a reliability indicator of primary importance for improving system reliability at both the design and the operation stages.

Redundancy is classified into time, structural (hardware), and information redundancy. The developed MPAB system is a repairable system with structural redundancy (loaded, or "hot", standby): the control and power-supply subsystems at each station are dual-channel, and the interstation communication is dupli-

cated via wired and optical channels. The operation of a redundant repairable system is a random Markov process with discrete states. The state graph of such a system is shown in Figure 4. The graph represents three states of the system:

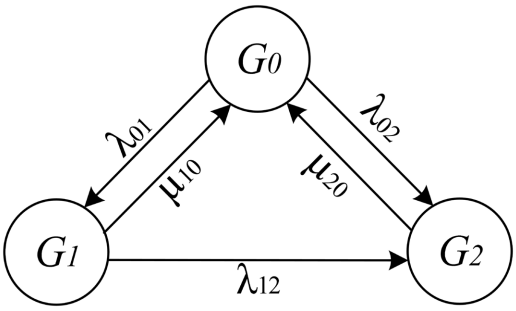


Figure 4. State graph of the redundant repairable system.

G_0—fully operational state (both channels are functioning);

G_1—faulty but operable state (one of the channels has failed, and the system operates via the other channel);

G_2—inoperable state (both channels, or an element common to both channels, have failed).

The system passes from one state to another under the action of failure and restoration flows. The random process governing these transitions is a Markov process described by a system of differential equations [3]. The system of equations is constructed from the state graph according to the following rule: the derivative of the probability of a state equals the sum of as many terms as there are arrows connected to that state; each term equals the product of the intensity of the event flow acting along the arrow and the probability of the state from which the arrow originates; if the arrow leaves the given state, the term is taken with a minus sign:

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} = -(\lambda_{01} + \lambda_{02})P_0(t) + \mu_{10}P_1(t) + \mu_{20}P_2(t); \tag{3}$$

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} = \lambda_{01}P_0(t) - (\lambda_{12} + \mu_{10})P_1(t); \tag{4}$$

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} = \lambda_{02}P_0(t) + \lambda_{12}P_1(t) - \mu_{20}P_2(t). \tag{5}$$

where λ_{01} is the transition rate from the fully operational state to the faulty but operable state; λ_{02} is the transition rate from the fully operational state to the inoperable state; λ_{12} is the transition rate from the faulty but operable state to the inoperable state; μ_{10} is the restoration rate from the faulty but operable state to the fully operational state; μ_{20} is the restoration rate from the inoperable state to the fully operational state; $P_0(t)$, $P_1(t)$, and $P_2(t)$ are the probabilities that the system is in states G_0, G_1, and G_2, respectively, at time t.

The state to which a particular failure transfers the MPAB system follows from the system structure. A failure of an element within one channel (microcontroller,

input/output module, interposing relay, power-supply unit, etc.) transfers the system to state G_1, since the other channel continues to perform the function in full. A failure of elements common to both channels (HMШ2-900 safety relays, UPS, network switch) transfers the system directly to state G_2. Accordingly, if the failure rate of one channel is λ_{ch} and that of the common elements is λ_{com}, then:

$$\lambda_{01} = 2\lambda_{ch};\ \lambda_{02} = \lambda_{com};\ \lambda_{12} = \lambda_{ch} + \lambda_{com}. \tag{6}$$

When reliability up to the first failure is assessed, state G_2 is treated as an absorbing state ($\mu_{20} = 0$). As in standard calculations, the estimate given below is obtained without considering restoration ($\mu_{10} = 0$); this estimate provides a lower bound on system reliability.

The general structure of the MPAB system is shown in **Figure 2**. The system equipment is housed in cabinets at stations A and B, and the composition of the equipment at both stations is identical. Communication between the stations is provided via wired and optical communication systems. Most of the legacy HMШ relays have been dismantled, and only the HMШ2-900 relays have been retained for safety functions. Power is supplied through 220/24 V power-supply units and a UPS; the cabinet is equipped with cooling fans for hot conditions and a heater for cold conditions.

For ease of calculation, the system is divided into three subsystems from the reliability standpoint: the control-logic (CL) subsystem at each station, the power-supply (PS) subsystem, and the interstation communication subsystem. For each subsystem, the probability of failure-free operation is expressed as:

$$P_s(t) = P_{com}(t) \cdot \left[1 - \left(1 - P_{ch}(t)\right)^{m+1}\right] \tag{7}$$

where $P_s(t)$ is the probability of failure-free operation of the subsystem; $P_{ch}(t)$ is the probability of failure-free operation of each channel; $P_{com}(t)$ is the probability of failure-free operation of the elements common to the channels; m is the redundancy multiplicity (m = 1 for the MPAB system).

The probability of failure-free operation of each channel of a redundant subsystem equals the product of the probabilities of failure-free operation of the elements forming that channel.

In Equation (6), the wired and optical communication links are assumed to have identical reliability for the purposes of simplifying the analytical model. This assumption does not imply that the actual failure characteristics of the two links are physically identical. The links differ in their transmission media and operating characteristics; however, a common reliability representation is adopted in the present model to simplify the system-level assessment. Therefore, the results should be interpreted in the context of this modelling assumption, and the potential effect of differences between the two communication links should be considered when evaluating the accuracy of the reliability estimates. Assuming that element failures follow the exponential distribution law:

$$P_{ch}(t) = \prod_{i=1}^{N} P_i(t)^{n_i} = e^{-\sum_{i=1}^{N} n_i \lambda_i t} \tag{8}$$

where n_i is the number of elements of type i; λ_i is the failure rate of an element of type i, 1/h.

The component failure rates used in the reliability assessment were obtained from manufacturer documentation and published reference literature on railway signalling and centralization equipment. The source used for each component and the basis for adopting its failure-rate value are identified individually in Table 1. Where a manufacturer provides a mean time between failures (MTBF), the corresponding constant failure rate is estimated using $\lambda = 1/T_{\mathrm{MTBF}}$, provided that the assumptions underlying this conversion are applicable [4] [8]. Manufacturer reliability figures are interpreted according to their stated operating conditions, environmental limits, service life, and maintenance assumptions. Functional-safety indicators, such as the average frequency of dangerous failures (PFH), are not treated as interchangeable with an all-mode component failure rate unless their definitions and applicability to the present reliability model are demonstrated [7]. Where a directly applicable manufacturer MTBF value is unavailable, the adopted failure rate is taken from the cited technical reference or is explicitly identified as an engineering assumption. The source and justification for each adopted value are provided in Table 1. The structural redundancy diagram of the control-logic subsystem in each station cabinet is shown in Figure 5. Each channel consists of a fail-safe S7-1200 microcontroller, two DI/DQ modules, and five PLC-24/U-21 micro-relays (ten per station); three HMШ2-900 safety relays are common to both channels.

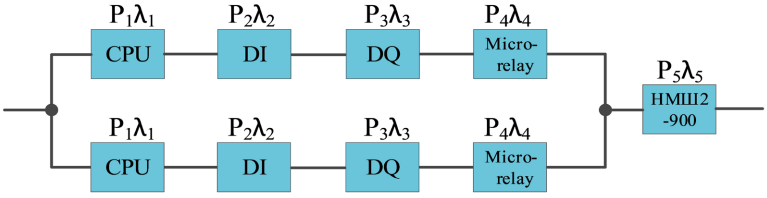


Figure 5. Structural redundancy diagram of the control-logic subsystem.

Table 1. Failure rates of the control-logic subsystem elements (one station).

№	Element	Total per station	Per channel, n	$\lambda_i \cdot 10^{-6}$, 1/h	$n \cdot \lambda_i \cdot 10^{-6}$, 1/h
1	S7-1200 F microcontroller (CPU)	2	1	2.50	2.50
2	S7-1200 DI module	2	1	1.00	2.00
	S7-1200 DQ module	2	1		
3	Phoenix Contact PLC-24/U-21 relays	10	5	0.50	2.50
4	HMШ2-900 relays		3	1.00	3.00
	Total (one channel/common)				7.00/3.00

To improve the reproducibility of the reliability assessment, the power-supply, interstation communication, and relay-based comparison systems are described

in terms of their constituent components. For each subsystem, the component inventory, quantity, adopted failure intensity, and data source are specified separately. Redundant channel elements are distinguished from common elements whose failure may affect both channels. These component-level inputs are used in the system-level reliability calculations to account for channel redundancy and failures of shared elements.

Using Table 1, the failure rates of one channel and of the common elements are obtained:

$$\lambda_{\text{ch.CL}} = \lambda_1 + 2\lambda_2 + 5\lambda_3 = 7.0\times10^{-6}\ 1/\text{h}; \tag{9}$$

$$\lambda_{\text{com.CL}} = 3\lambda_4 = 3.0\times10^{-6}\ 1/\text{h}. \tag{10}$$

The mean time to first failure of the subsystem is:

$$T_{\text{CL}} = \int_0^\infty P_{\text{CL}}(t)\,\text{d}t = \frac{2}{\lambda_{\text{ch.CL}} + \lambda_{\text{com.CL}}} - \frac{1}{2\lambda_{\text{ch.CL}} + \lambda_{\text{com.CL}}} = 141176\ \text{h} \tag{11}$$

$$T_{\text{CL}} = 141176\ \text{h} \approx 16\ \text{years}\ 1\ \text{month}.$$

The time dependences of the probability of failure-free operation and the probability of failure of the control-logic subsystem are shown in Figure 6.

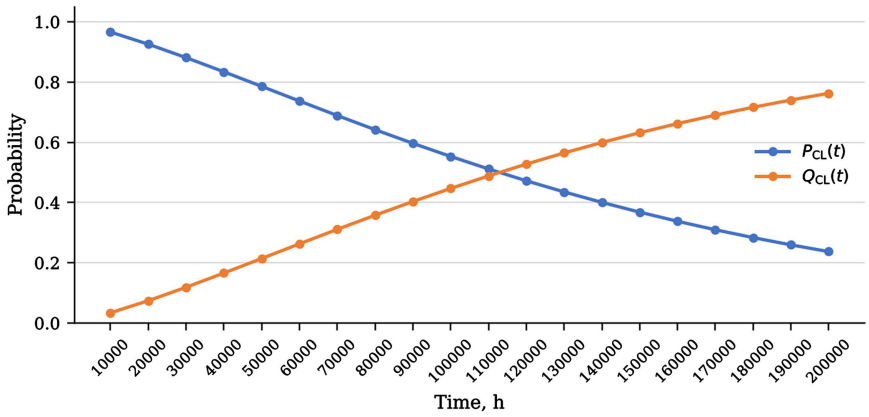


Figure 6. Time dependences of PCL(t) and QCL(t).

The power-supply and interstation communication subsystems are calculated in the same manner using Equations (7) and (8). Since a failure of any subsystem results in a failure of the MPAB system as a whole, the subsystems are connected in series from the reliability standpoint, and the probability of failure-free operation of the entire system is:

$$P_{\text{MPAB}}(t) = \prod_{j=1}^{K} P_j(t), \tag{12}$$

where $P_j(t)$ is the probability of failure-free operation of the j-th subsystem; K is the number of subsystems ($K = 5$: the control-logic and power-supply subsystems of stations A and B and the interstation communication subsystem). The mean time to first failure of the system is then determined as:

$$T_{\text{MPAB}} = \int_0^\infty P_{\text{MPAB}}(t)\,\text{d}t. \tag{13}$$

The calculation yields a mean time to first failure of the MPAB system of T_{MPAB} = 36,272 h, whereas for the conventional relay-based semi-automatic block system, calculated by the same method, it is T_{rel} = 12,987 h. Thus, the proposed structure increases the mean time to first failure by a factor of approximately 2.8.

In the reliability assessment, component failures are assumed to be statistically independent unless they are associated with shared elements or common-cause events. A constant failure rate is assumed for each component during the period of analysis, allowing the exponential reliability model to be applied. The redundant control channels are considered capable of maintaining system operation following a single-channel failure, provided that the remaining channel is operational and the changeover mechanism functions correctly. However, redundancy does not eliminate the effects of common-cause failures, including shared software faults, common power-supply failures, and adverse environmental conditions. Such effects are considered through the corresponding common-element failure rates where these are included in the model. These assumptions should be taken into account when interpreting the calculated reliability values.

The boundary of the reliability model is limited to the components explicitly represented in the system structure and reliability calculations, including the microprocessor-based control logic, communication channels, power-supply subsystem, and the shared elements considered in the model. Axle counters, operator interfaces, and cabinet temperature-control devices are not included in the present reliability assessment. Consequently, failures of these devices and their potential effects on overall system reliability are not reflected in the calculated reliability estimates. This limitation should be considered when interpreting the results.

4. Conclusions

This paper has presented the structural design and reliability assessment of a microprocessor-based semi-automatic block (MPAB) system for railway transport. The main results are as follows.

1) A structural diagram of the MPAB system has been developed. The system consists of two symmetric half-sets located at the stations bounding the line section; the control-logic and power-supply subsystems at each station are dual-channel with hot standby, and the interstation communication is duplicated via wired and optical channels.

2) A three-state Markov model of a redundant repairable system has been applied to the reliability assessment. A failure within one channel transfers the system to a faulty but operable state, whereas a failure of an element common to both channels leads directly to the inoperable state.

3) For the control-logic subsystem, the failure rates of one channel and of the common elements are 7.0×10^{-6} and 3.0×10^{-6} 1/h, respectively, and the mean time to first failure is 141,176 h (approximately 16 years).

4) The mean time to first failure of the MPAB system as a whole is 36,272 h, which is approximately 2.8 times higher than that of the conventional relay-based

system (12,987 h). These results confirm that structural redundancy combined with microprocessor-based control improves the reliability of railway blocking systems.

Since the obtained estimates do not take restoration into account, they represent a lower bound on system reliability. Further research will address reliability assessment with restoration ($\mu_{10}, \mu_{20} \neq 0$), functional safety analysis, and the testing and technical operation of the remaining relay-contact circuits [9] [10].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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