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THE SAFETY OF RAILWAY TRANSPORT SYSTEMS – THE HISTORICAL AND ACTUAL STUDY

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Abstract – The paper presents the evolution of safety concept assigned to railway transport with respect to management and control of trains. The first step was introduction of electrical systems based on fail-safe relay interlocking. The next stage is electronic, computer systems with decision part based on implementation of correct algorithms related to EU standards. The main rule of safety control and management corresponds to Tolerable Hazard Rate (THR). The next stage was introducing to the railway interlocking and management systems the open radio transmission such Internet, GPS or GSM (version GSM-R). For safety analysis the recommended mathematical methods such Markov processes may be applied, the example of safety analysis of ERTMS/ETCS system is presented in the paper.

Key words – Safety of Railway Control and Management Systems, SIL and safety criteria, THR and FFFR, ERTMS/ETCS, Markov models of railway control processes

JEL Classification – L92, N70, R40

INTRODUCTION

Fail – Safe Relay Interlocking

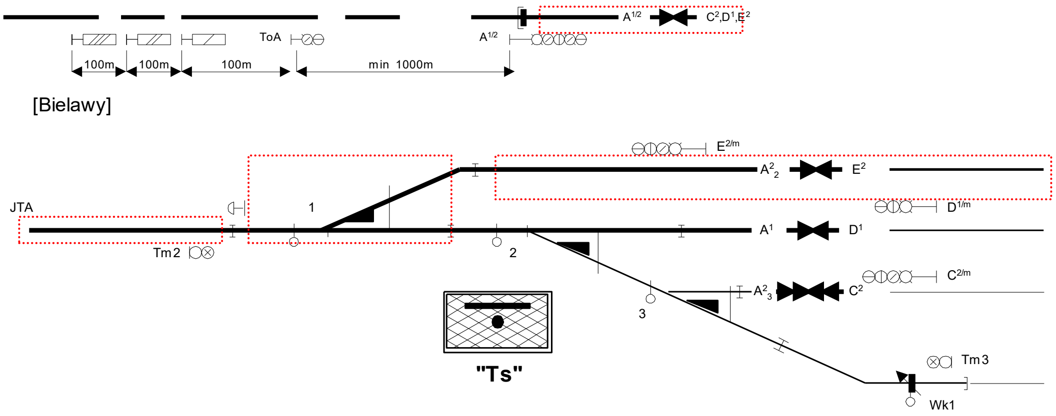
The introduced in first years of XX century the relay solutions in interlocking have eliminated the fault during design process of dispatcher desk. The relay interlocking systems were designed with respect to *fail-safe* rule: any single fault in the system does not lead to faulty control of external devices (signaling or point/switch). The single fault must ensure the change of system state to safety state (impossible to set the permitted signal, switch the point, set the route). It generates some restrictions in interlocking control but eliminates the non-safety situations. The fail-safe rule assumes the detection of each critical failure leads to safety reaction procedure assures the achievement of safety state. In the practice the fail-safe rule bases on relays I(N) class with asymmetric characteristic of failure (probability of fault 0→1 connected with start of current in relay coil not is significantly high)

The safety of electric circuits is realized by special components such special construction of output relays or special design of electrical circuits. Both methods have been implemented in polish railways [3]: individual design corresponding to special encoding of dependencies table (system E) and module oriented geographical design (graph of relation between functional modules in IZH 111, CBP83, SUP3 systems).

The all connections in E system (Fig. 1.a) assigned to Table of Interlocking, the each route is monitored direct for station area corresponding to four electrical circuits (setting, signaling, validation and releasing, signaling and lighting). The E system assures the individual control and monitoring of all insulated rail sections and points, and exclusives all conflicts in station area.

The geographical system JZH 111 (Fig. 1.b) is built with specially designed typical relay blocks assigned to appropriate railway devices such point, signaling, etc. , realized in standard relay module. The connections between modules are logical relations realize choice of route, setting the elements of route, validation of choose the appropriate modules, etc.

a)



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2	A^1_1	Ze st. Bielawy na tor 1	+	—	+		+	+	+			+							+	+	+	+		+	+	+	+				+				+			+	+	$+_o$	$+_o$					A,1	1,2
3	A^2_2	Ze st. Bielawy na tor 2	+	+	—		+	+	+				+						+	+	+	+		+	+	+	+					+				+		—								A,2	1

b)

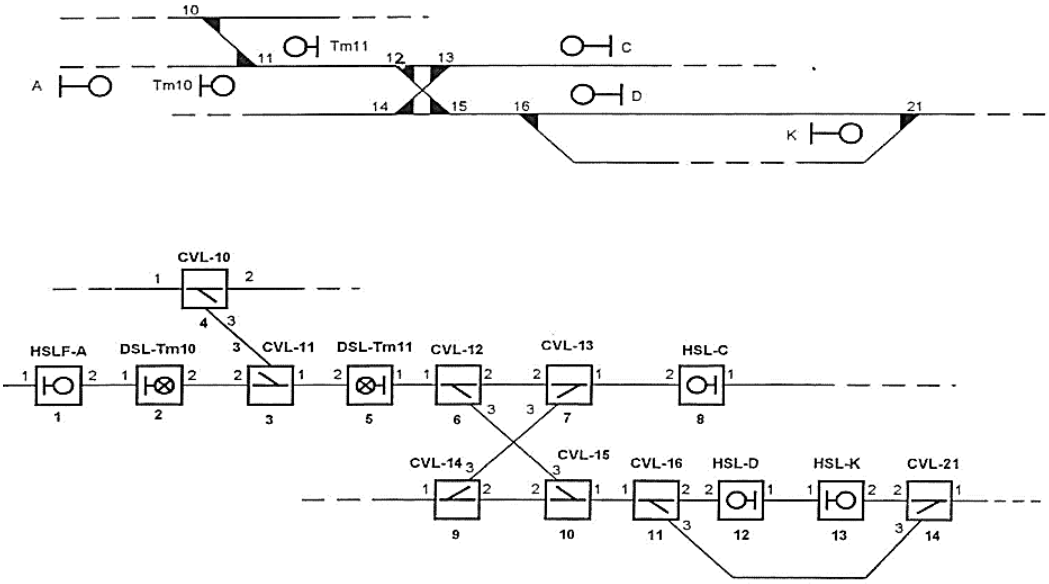

Fig. 1. The relay interlocking systems a) The example of rail configuration with corresponding the Table of Interlocking (E) b) The example of rail configuration in the station with geographical approach (JZH 111) [3]

Both relay interlocking systems typical for polish railways have been characterized by high reliability, assumed functionality and maintainability (rather extensive with respect to production and service of specially designed relays).

1. THR AS A MEASURE OF INTENSITY OF CRITICAL FAILURES EU STANDARDS AND RECOMMENDATIONS

The safety of railway relay interlocking systems is related to characteristics of electro-magnetic relay with non-symmetric failures 1→0 and 0→1. For computer control systems the failures have symmetric characteristics, this rule of design of design assumes the tolerable hazard rate and the multi-channel data processing (2 of 2 or 2 of 3). The single channel realization of railway control systems applies the input/output diagnostics functions, coding and special software procedures. For double or triple realization of such systems the hardware and software redundancy with special voting/comparison data in channels must be applied.

The Table I shows the appropriate failure rates for European railway administrations, systems, subsystems and elements corresponding to tolerable risk philosophy.

Table 1. The failure rates for railway control systems based on UIC/TC-ITSE [12]

Assumptions	**Hazardous failure rate (per hour) [h^{-1}]**
Tolerable railway accident rate due to hazardous technical failure = 1 per year in whole of Europe	**10^{-4}** For whole of European railway system technical installations.
1 hazardous technical failure in 10 leads to an accident.	**10^{-3}** For whole of European railway system technical installations.
1 technical failure in 10 is a **signalling** failure.	**10^{-4}** For whole of European railway **signalling** installations.
Safety margin 10:1 to allow for uncertainties and tolerances.	**10^{-5}** For whole of European railway signalling installations.
1000 complete signalling systems in whole of Europe.	**10^{-8}** Per complete signalling system. (e.g. major traffic route or area)
10 sub-systems per complete signalling system.	**10^{-9}** Per signalling subsystem. (e.g. large interlocking)
100 system elements per signalling sub-system.	**10^{-11}** Per system element. (e.g. train detection, point control or signal control function)
Ratio of 100:1 between each safety Integrity Level.	**10^{-11}** (for System Integrity Level 4) **10^{-9}** (for System Integrity Level 3) **10^{-7}** (for System Integrity Level 2) **10^{-5}** (for System Integrity Level 1)

Such decomposition of safety related systems is recommended by railway authorities from UIC/IRSE [12] and safety systems specialists from standardisation committees CEN/CENELEC .

The level 4 is related to interlocking systems, the level3 to ATP/ATC systems, dispatcher control and industrial depot control. The level 2 systems are represented by computer visualisation (computer desk) including implementation in relay systems. The level 1 connected with ticket and time table systems (computer nets with protection of data), the non-safety related level 0 systems are typical information station systems without special protection of data.

The idea of safety redundant systems assumes the low intensity of hardware failures and independence of processing channels (significantly low probability of double or multiple faults).

The classification of railway safety systems is presented in the Table 2.

Table 2. The system classification based on UIC/TC-ITSE [12]

System level	Required integrity of safety	Characteristics of system	Consequences of system fault
4	Very high	To prevent the train collision and derailment	Loss of human life
3	High	To identify the integrity or characteristics of train	Injuries or illness
2	Medium	To manage the railway traffic	Environmental pollution
1	Low	To inform the passenger	Loss or damage of property
0	Non-safety related	To manage the railway	Loss of non-safety related information

The intensity of failures assigned to each SIL level is defined as Tolerable Hazard Rate (THR) and obligatory for designers of computer interlocking devices (standards **EN 50126** [13] and **PN-EN 50129** 14]).

The standard **EN 50126** [13] defines Reliability, Availability, Maintainability and Safety (RAMS) with respect to system life cycle(specification, requirements, design, implementation, validation, etc.). The standard **PN-EN 50129** [14] is connected with requirements of design, testing and validation of electronic components applied in railway interlocking safety systems. The **EN 50128** [15] defines the methods, procedures and technical requirements related with software for safety systems.

The THR is defined as follows:

$$\mathrm{THR} = \prod_{i=1}^{n} \frac{\lambda_i}{t_{d_i}^{-1}} \cdot \sum_{i=1}^{n} t_{d_i}^{-1} \tag{1}$$

where: λ_i– i san intensity of failures for channel i, and t_{di} is a time of reaction for system for detected fault in channel *i*.

The t_{di} may be approximated as a sum of 0.5 time of controller cycle and time of reaction after detection of fault of input or output

It means that intensity of critical failures described by THR is reduced by $2t_d/t_{TF}$, where t_d is time reaction for failure and t_{TF} is a mean time of failure in given channel.

The THR value for each SIL level may be acceptable as follows:

for SIL4 $10^{-9} \le \mathrm{THR} < 10^{-8}$

for SIL3 $10^{-8} \le \mathrm{THR} < 10^{-7}$

for SIL2 $10^{-7} \le \mathrm{THR} < 10^{-6}$

for SIL1 $10^{-6} \le \mathrm{THR} < 10^{-5}$

The standard requires the determination of time of single faults

$$T_{sf} = \frac{k}{1000 \cdot \lambda} \tag{2}$$

and double faults

$$T_{2sf} = \frac{2}{\lambda} \tag{3}$$

where: *k* is a coefficient of redundancy (1 for systems 2 of 2 and 0.5 for systems 2 of 3)", λ is a sum of average intensities of failures the elements may cause the critical fault.

For analysis of systems composed with configuration of serial elements the total intensity of failures is equal to:

$$\lambda_0 = \lambda_1 + \lambda_2 + \ldots + \lambda_i = \sum_{i=1}^{n} \lambda_i \tag{4}$$

In parallel configuration of elements is possible the determination of mean time to failure with respect to known such time for each elements:

$$T_{MTF} = \sum_{i=1}^{n} \frac{1}{\frac{1}{t_{Fi}}} - \sum_{i,j=1}^{n} \frac{1}{\frac{1}{t_{Fi}} + \frac{1}{t_{Fj}}} + \sum_{i,j,k=1}^{n} \frac{1}{\frac{1}{t_{Fi}} + \frac{1}{t_{Fj}} \frac{1}{t_{Fk}}} + \ldots + (-1)^{n} \frac{1}{\sum_{i=1}^{n} \frac{1}{t_{Fi}}} \tag{5}$$

using the following approximation:

$$T_{Fi} = \int_{0}^{\infty} R_i(t)dt = \int_{0}^{\infty} e^{-\lambda_i t}dt = \frac{1}{\lambda_i} \tag{6}$$

As an example the system of cross level signaling system produced by KOMBUD S.A. [10] assigned to SIL 4 may be analyzed with respect to THR. It is 2 channel system with two identical independent PLC controllers communicate via ETHERNET (Fig. 2). Each controller contains:

- Base rack IC695CHS012, 761 000 [h]
- Power supply IC695PSD140, 092 000 [h]
- CPU IC695CPU310, 638 000 [h]
- Communication interface IC695ETM001), 992 000 [h]
- Modules of discrete inputs IC694MDL660), 6 393 000 [h]
- Modules of discrete outputs IC694MDL754), 553 000 [h]

For this equipment the value pf Mean Time To Failure (MTTF equivalent to 1/*λ)* i given by producer (Astor Kraków) using laboratory tests is attached of PLC modules.

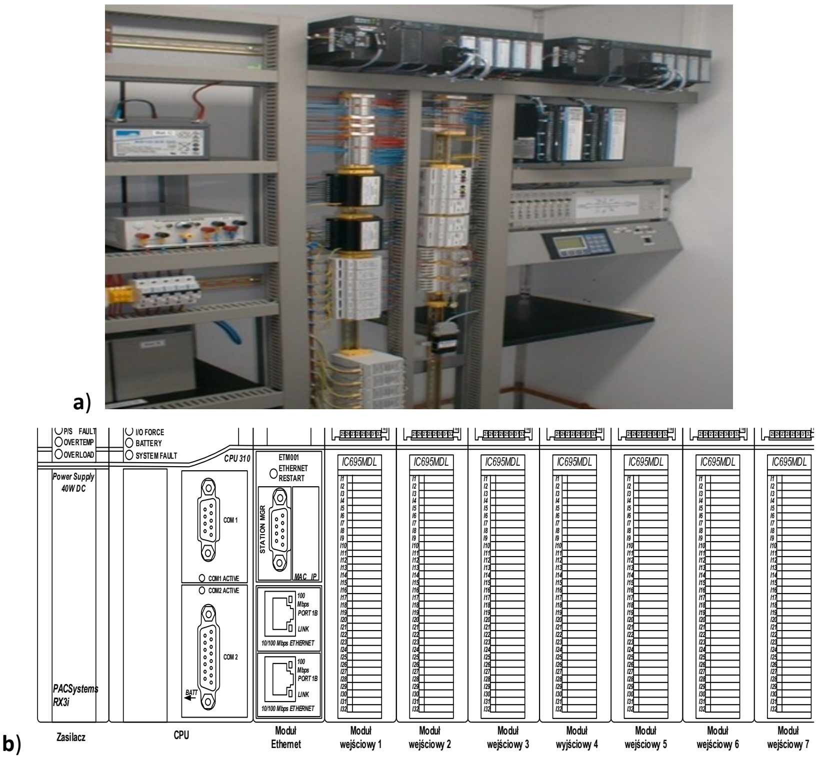

Fig. 2. Two channel realization of cross level signaling system with PLC controllers a) the view of implemented system b) the scheme of PLC controller [5]

The presented PLC configuration contains 6 input and 2 output modules. The serial structure of PLC controller allows to estimate MTTF as 106 832.6186 [h]. The t_{sf} is rather low (The time of cyclic testing of inputs and outputs – 500 ms, the time of reaction for failure – 1s) than the t_{di} is 1,250s and THR value is less than 2.19e-13 according to requirements for SIL 4 presented in PN-EN 50129 standard for 2 of 2 system. The THR coefficient may be elaborated using

- Data from exploitation of now implemented systems (8-10 years),
- Data from prognostic procedure of new designed systems (MIL standard).

All presented methods are detailed presented in [5].

2. NEW SAFETY RECOMMENDATIONS OF RAILWAY TRANSPORT

From 2019 in UE has been implemented The Safety Management System (SMS) related both to railway infrastructure and operator of trains. The main assumption of introduced regulations is documentation of railway system safety including all changes corresponding to monitored maintenance. The main part of The SMS is risk analysis and introduced procedures of risk reduction. The mentioned IV Railway Package include appropriate standards and regulations of EU Railway Agency, Commissions of EU (including EU Council and Parliament) connected with liberalization and deregulation of train freights and certification of railway systems. The obligatory for safety analysis are standards EN 50126 (part 1 and 2)/2017 and PN-EN 50129/2018 presented on Figure 3 .

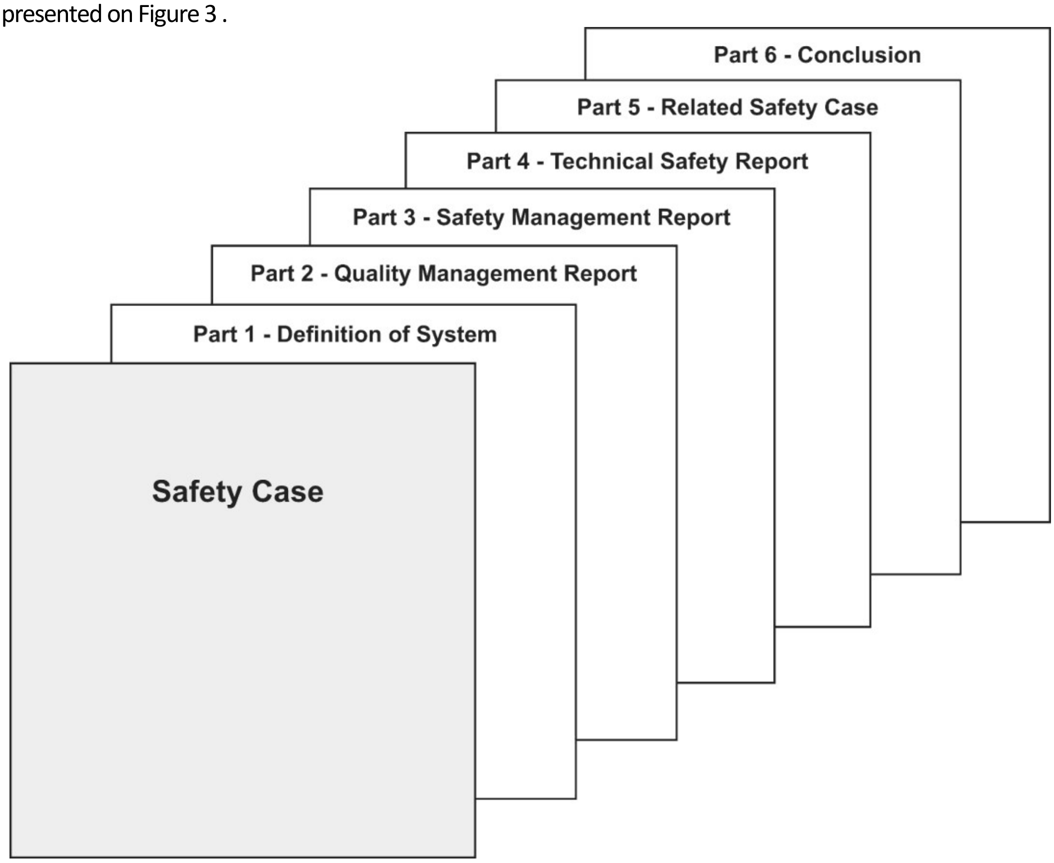

Fig. 3. The structure of safety proof documentation with respect to EU standards 50126 [13] **and 50129** [14]

The new measure of safety is Tolerable Functional Failure Rate (TFFR) instead of previous THR criterion, related to infrastructure and trim devices failures (Fig. 4).

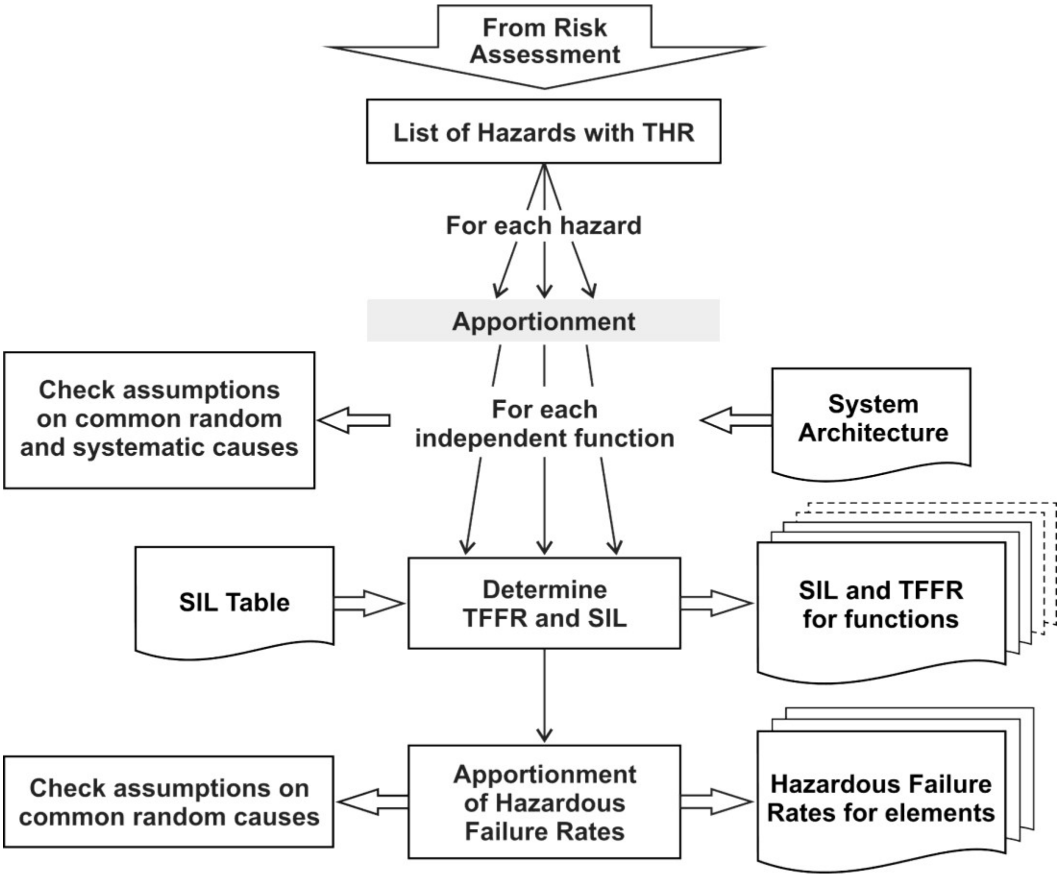

Fig. 4. The method of determination of TFFR corresponding to evaluated the THR for subsystems [14]

The method of determination the TFFR corresponding to known THR values may respect the rules of co-operatin of subsystems (for example ETCS and SHP) and human factor (measurable time of reaction of train operator for presented visualized data from subsystems in deck computer). The determined values of TFFR must correspond to SIL requirements [5].

The next problem was introduction the open transmission standards to railway interlocking and management. The public wireless (radio) connections may be applied with respect to obligatory **EU 50 159** Standard [16] with requirements of information protection (coding).

3. THE PROBABILITY OF CRITICAL FAULT – THE ERTMS/ETC ANALYSIS

The very good example of new safety system requirements is ETCS European Train Control Systems, defined with respect to 3 levels of train control and monitoring [9]. The rail infrastructure regards new devices – balises (Eurobalises) [11] built in rails for communication with train. The vehicle is equipped in special devices to communication with balise, processing of data and visualization via desk computer. The safety is improved by monitoring of train movement corresponding to telegrams from Radio Center (using GSM-R standard) and safety reaction for detected faults. The ETCS may co-operate with existing ATC systems (such SHP in polish railways) The elements of the ETCS system [4], [6] are shown in Figure 6. These new elements are: 1 - driver's interface, 2 - antenna for track-vehicle transmission (mounted in the locomotive), 3 - eurobalise, 4 - GSM-R system, 5 - relay interface unit, 6 - on-board (desk) computer and 7 - data recording module.

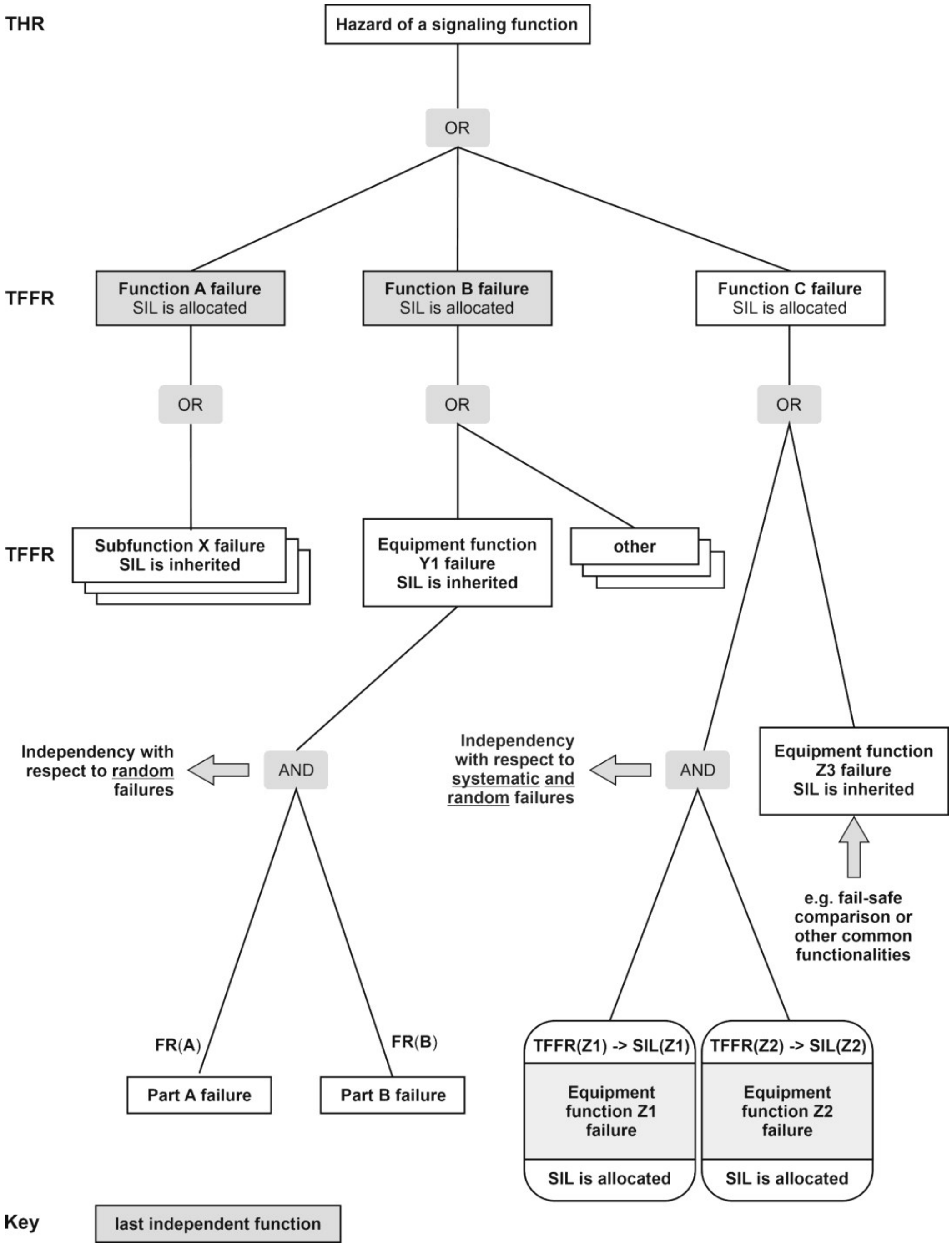

Fig. 5. Relations between TFFR and THR with respect to 50126/2017 standard [13]

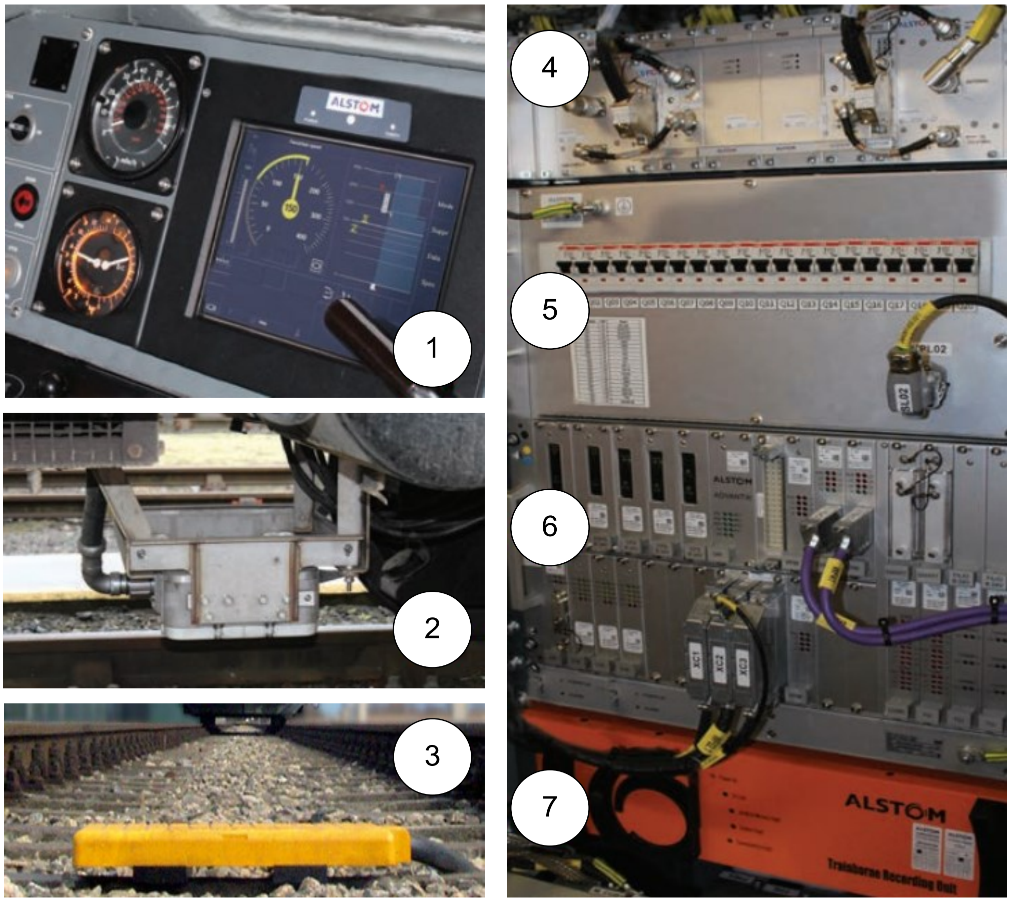

Fig. 6. Elements of the ETCS system (own study based on [6])

In the standards related to safety railway system including the infrastructure and vehicle devices as a supplementary method of safety analysis the several methods are recommended. The good example may be application of Markov Processes for estimation of critical (catastrophic) failures. Presented example corresponds to ETCS Level 1 implementation in Polish Railway, which significant increases the safety using monitoring of train operator work.

The detailed description of ERTMS/ETCS levels [8] contains the regulation of compatibility on board devices to bottom down – the train equipped with Level 3 devices may drive in the lines of Level2 or 1 and lines without eurobalises. Thus ETCS system may be treated as intelligent overlay on existing interlocking systems. The Level 1 devices (may be equipped with eurobalises) for communication with train) assume that train cannot pass the prohibited track and must regard the permitted speed. In the Level 2 communication is extended to radio control center (RBC), the semaphores for visual communication with train operator may be eliminated – the information is transmitted via radio channel. The Level 3 is evolution the Level 2 towards changeable block distance, the control in fracture may be eliminated from rail circuits and axe counters. The level 3 assures the implementation of changeable block distance [3] and drive with "electrical visability".

For safety analysis the following basic model of train control is introduced [8], [9] The simple model from Figure 7 is based on homogenous, stationary and ergodic Markov process [6]. The introduced states corresponds to following train control situations:

0 – the correct drive of train with respect to last received information , the train operator driving the train corresponding to received permission for drive, the procedure assume the continuation of drive corresponding to next received permission from dispatcher,
1 – the state of correct realization the control/monitoring procedure (with respect to signaling visualization corresponding to signaling device or on-board computer,
2 – the state of emergency stop or speed reduction related to existing situation without control/monitoring (emergency breaking enforced by ATP system).

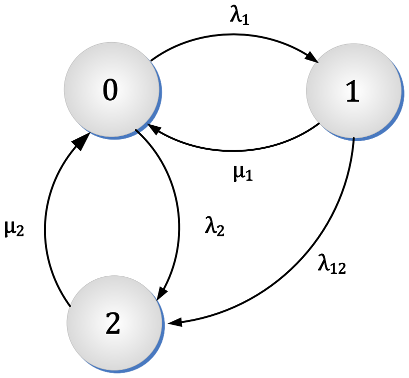

Fig. 7. The basic model of train control corresponding to Markov process [6]

The transitions between states are connected with the events described as typical parameters of railway interlocking devices. The appropriate different equations are as follows:

$$\begin{cases} \dfrac{dP_0(t)}{dt} = -\lambda_1 P_0(t) + \mu P_1(t) - \lambda P_0(t) + \mu_2 P_2(t) \\ \dfrac{dP_1(t)}{dt} = \lambda_1 P_0(t) - \lambda_{12} P_1(t) - \mu_1 P_1(t) \\ \dfrac{dP_2(t)}{dt} = \lambda_{12} P_1(t) - \mu_2 P_2(t) + \lambda_2 P_0(t) \end{cases} \tag{7}$$

with initial condition

$$P_o(t) + P_1(t) + P_2(t) = 0\,, \ (\textit{for } t{=}0) \tag{8}$$

For safety analysis the boundary probability of P_2 is important:

$$\begin{aligned} P_0 &= P_0(t)\,|_{t\to\infty} = \frac{(\lambda_{12}+\mu_1)\mu_2}{(\lambda_{12}+\mu_1)(\lambda_2+\mu_2)+\lambda_1(\lambda_{12}+\mu_2)} \\ P_1 &= P_1(t)\,|_{t\to\infty} \ \frac{\lambda_1\mu_2}{(\lambda_{12}+\mu_1)(\lambda+\mu_2)+\lambda_1(\lambda_{12}+\mu_2)} \\ P_N &= P_N(t)\,|_{t\to\infty} = \frac{\lambda_1\lambda_{12}+\lambda_2(\lambda_{12}+\mu_1}{(\lambda_{12}+\mu_1)(\lambda+\mu_2)+\lambda_1(\lambda_{12}+\mu_2)} \end{aligned} \tag{9}$$

These parameters for the basic model may generally interpreted as:

- λ_1 - Intensity of events connected with start drive of train after permission signal or received permission of drive (MA) and received next drive procedure,,
- λ_{12} - intensity of event connected with faulty reaction of train driver or improper action of ATP system,
- λ_2 - intensity of events connected with implementation of emergency breaking system (without train driver action) up to completely stop of train,
- μ_1^{-1} - time necessary to information signal for train driver about next action – drive procedure of the train with respect to safety requirements,
- μ_2^{-1} - minimal time necessary for train driver to star after automatic (emergency) stop of train.

In the existing interlocking devices based on fixed block distance the occupation of next block distances (insulated rail sections) is realized with respect to permission signal with simultaneous information about occupancy the rail section by succeed train (he supervised sequence of events corresponding to succeed and next train). Thus the functionality of railway line is connected with possibility of occupation of sequence the rail sections.

Corresponding to introduced model the following assumption for fixed block distance are assumed:

The maximal of block distance is 1500 m (minimal 1300m), the maximal speed is 160km/h and λ I and μ parameters are assumed as follows [6]:

- λ_1 - intensity of recommended train drives with respect to correct received permits drive 106,67h^{-1} (corresponding to required time of waiting for permitted signal 33,75s),
- μ_1 - intensity of typical service by train 300 h^{-1} (reciprocal to time of service 12s),
- λ_2 - intensity of faulty interpretation with respect to (failure index) 0,000227687 h^{-1} (connected with occurrence the2 drives of train in one year),
- λ_{12} - intensity of faulty interpretations with respect to requirements (failure index) 0,005952381 h^{-1} (connected with time of emergency drives of trains 1 in the week),
- μ_2 - intensity of faulty service 72 h^{-1} (reciprocal to time of service of fault50 s).

The evaluation of critical failure in fixed block distance interlocking corresponding to formula (9) is equal to $\mathbf{P_2 = P_{2FBD} = 2{,}401 \cdot 10^{-5}}$.

Now the analysis of ETRMS/ETCS Level 1 allows to estimate of adequate the critical failure. The on board computer in the trains receives the permission for drive from group of balises placed before signaling device [6].

Assuming in the ETCS level 1 the maximal length of block distance 1500 m and permitted speed of train 160 km/h the parameters in Markov model from Fig. 4 may be modified as follows:

- λ'_1 - intensity of connection before balise (or semaphore) is equal to λ_1=166,67h^{-1} (corresponding to time 21,6s),
- μ'_1 - intensity of service equal to 360000 h^{-1} (corresponding wit 10 ms time of service or synchronization after passing 1 m),
- λ'_{12} - intensity of faulty telegrams received from balises leading to stop the train equal to $0{,}33 \cdot 10^{-9}$/h ,
- λ'_2 - intensity of failure the on board devices (with respect to THR requirement for deck devices) 1×10^{-9},
- μ'_2 - intensity of switch on the on-board devices to dedicated mode for trains not equipped 0,03333 h (connected with time of introducing the drive in not equipped mode z 120 s).

After evaluation corresponding to formula (9) the probability of critical failure for ERTMS/ETCS Level 1 is equall to $\mathbf{P_2 = P_{2ETCS\,L1} = 3{,}003 \cdot 10^{-8}}$.

This example evidently shows the advantage of new technology ERTMS (ETCS Level 1) with respect to previous fixed block distance interlocking. Both infrastructure and train on-board train devices must respect the safety requirements of SIL 4, similarly such computer interlocking with insulated rail sections. The presented method (Markov processes) is highly recommended by EU standards (EN 50 128 [15]. The safety analysis of several ETCS Levels using Markov processes is presented in works {7] (level 2) and [7] (level 3). The short safety analysis of ETCS level 2 and 3 with presented model is presented in [6]. The main remark related to such publication shows that the recommended mathematical analysis based on stochastic processes (Markow processes) may be support for safety proof [1].

CONCLUSIONS

The paper shows the evolution of safety of railway control and management systems. The relay interlocking assumes the failure free construction of relays especially coding of output signals. The next – computer based on tolerable hazard rate measure including the hardware redundancy (2 of 2 or 2 of 3) and failure rates related to SIL classification. Introduced in 2011 extends the safety requirements for railway vehicles, The THR for whole system i(interlocking infrastructure and trains) may respect the adequate SIL 4 requirements. The very good example is ERTMS/ETCS system, the infrastructure is extended to eurobalises and radio centers for control and monitoring. The introduced ETCS Level 1 (in polish railways too) increases the functionality (capability) of railway lines. The paper shows that SIL restrictions increases the safety- the probability of catastrophic failure is signifantly reduced, the recommended method based on Markov process analysis may be extended for Levels 2 and 3 corresponding to including the parameters of Great Speed infrastructures (TGV, ICE, etc.) The presented Markov model is rather simple, buy may extended towards the more complicated states and transitions.

BEZPIECZEŃSTWO SYSTEMÓW TRANSPORTU KOLEJOWEGO - STUDIUM HISTORYCZNE I AKTUALNE

W pracy przedstawiona została ewolucja pojęcia bezpieczeństwa transportu kolejowego z uwzględnieniem zarządzania i sterowania ruchem kolejowym. Pierwszym takim krokiem było wprowadzenie systemów elektrycznych, opartych na tzw. bezpiecznych przekaźnikach. Kolejnym etapem było wprowadzenie systemów, elektronicznych – komputerowych, w których część decyzyjna wynikała z implementacji poprawnych algorytmów określonych w odpowiednich normach. Podstawowym założeniem w tych systemach było przyjęcie tolerowalnego poziomu ryzyka (ang. *Tolerable Hazard Rate*). Kolejnym etapem było wprowadzenie do zarządzania i sterowania ruchem kolejowym standardów transmisji otwartej, takich jak Internet, GPS czy GSM (wersja GSM-R). Do analizy bezpieczeństwa należało zastosować zalecane, złożone metody matematyczne takie jak procesy Markowa, dotyczy to na przykład systemu ERTMS/ETCS analizowanego w pracy.

Słowa kluczowe: bezpieczeństwo systemów SRK, klasyfikacja SIL i kryteria bezpieczeństwa, THR i FFFR, system ERTMS/ ETCS, modele Markowa procesów SRK

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