Functional safety of railway signaling systems: performance requirements and evaluation methods

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Signaling is fundamental to the safe operation of the railway, ensuring that trains are spaced safely apart and conflicting movements are avoided. Railway signals are ‘traffic light’ devices, which tell a train driver if it’s safe to proceed along the track. A railway signaling system consists of several complex subsystems, e.g. trackside- and onboard signaling systems, which cooperate to ensure the safe operation of railway traffic. The failure of signaling system will weaken both capacity and safety of the railway. It is therefore important to keep the railway signaling system complying with the defined performance requirements. The purpose of this study starts with the summarization of railway RAMS, focusing on railway signaling systems. The tolerable hazard rate (THR) which is an indicator of signaling system performance in EN 50129 (2018) has been compared with the similar indictor PFH (probability of failure per hour) for safety-related systems in IEC 61508 (2010). Based on the commonly used methods for safety-related systems in IEC 61508 (2010), several reliability modeling and analysis methods have been listed and reviewed for the specific system. This paper aims to provide clues for the engineers and analysts in the performance evaluation for the railway signaling system.

Keywords: Railway signaling system, performance assessment, tolerable hazard rate, probability of failure per hour.

1. Introduction

The railway industry has experienced significant changes during the past decades. Nowadays, they represent one of the most sustainable and ecologically friendly types of transport. Multiple countries put significant effort to improve interoperability and safety of their overall railway infrastructure. Depending on the functionality, the railway infrastructure can be divided into different system, e.g. the rolling stock, the track, the power supply and the signaling system so on(Pěnička 2007). These systems interact and lead to the complexity of railway systems. Thus, assuring their functional safety becomes a demanding task(Huld 2020).

Signaling is fundamental to the safe operation of the railway, ensuring that trains are spaced safely apart and conflicting movements are avoided. It is therefore vital to have a safe and reliable railway signaling system and keep its performance in every component complying with the predefined requirements. Considering the multiple subsystems and functions, a railway signaling system can be considered as a group of complex systems, with whose failures affecting both the capacity and safety of the railway. How to maintain the signaling system available is very

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important for the safe operation of rail. To specify and standardize the requirement, EN 50129 (2018) defines requirements for acceptance and approval of safety-related electronic systems in the railway signaling field. However, there is lack of systematic quantitative methods for signaling system performance assessment in EN 50129 (2018). Therefore, in this paper, several reliability analysis methods have been reviewed with reference to the probability of failure per hour (PFH) evaluation in IEC 61508 (2010), e.g. fault tree analysis, reliability block diagram, Markov methods and Petri net aiming to provide clues for the engineers and analysts in the performance evaluation for the railway signaling system.

The remainder of this paper is organized as follows: Section 2 introduces the RAMS in the context of railway; and then Section 3 presents the railway signaling system; Section 4 presents functional safety and tolerable functional hazard rate which is the main performance principle for railway signaling systems, and Section 5 reviews several reliability analysis methods which are listed in IEC 61508 (2010). The summary is presented in Section 6.

2. Railway RAMS

2.1. Elements of railway RAMS

RAMS here is the abbreviation of reliability, availability, maintainability, and safety. RAMS is a characteristic of a system's long term operation and is achieved by the application of established engineering concepts, methods, tools and techniques throughout the life cycle of the system (EN 50126 2017). The goal of a railway system is to achieve a defined level of rail traffic at a given time, safely and within certain cost limits. And the RAMS elements are interlinked in the sense that a weakness in any of them or mismanagement of conflicts between their requirements can prevent achievement of a dependable systems. The interrelation of railway RAMS elements depicted in EN 50126 (2017) is shown in Figure 1.

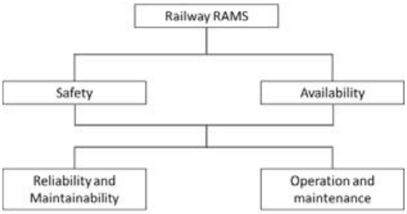


Figure 1 Interrelation of railway RAMS elements

(EN 50126 2017)

The definitions of RAMS are described in EN 50126 (2017) as:

- Reliability is the ability of an item to perform as required, without failure, for a given time interval, under given conditions;
- Availability is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided;
- Maintainability is the ability to retained in, or restored to, a state to perform as required, under given conditions of use and maintenance;
- Safety refers to the freedom from unacceptable risk.

2.2. Factors influencing railway RAMS

The RAMS performance of a railway system is influenced in three ways, that can interact:

- By sources of failure introduced internally within the system at any phase of the system life cycle;
- By sources of failure imposed on the system during operation; and
- By sources of failure imposed on the system during maintenance activities.

2.2.1. Classification of failures

Failures in a system, product or process are categorized as random failures or systematic failures. A major distinguish feature between these two failures is that random failures are in general due to events that can be statistically monitored so that their probability of occurrence can be estimated, while systematic failures are due to events for which statistical data is not usually available so that their probability of occurrence cannot generally be estimated, according to EN 50126 (2017).

While IEC distinguishes between random hardware failures and systematic faults, with treating software faults as a subclass of the systematic faults. For the random hardware failure, it refers to the failure occurred at a random time, which result from one or more of the possible degradation mechanisms in the hardware. And systematic failure can only be estimated by a modification of the design or of the manufacturing process, operational procedures, documentation, or other relevant factors (Rausand 2014; IEC 61508 2010).

2.2.2. Derivation of detailed railway specific influencing factors

In EN 50126 (2017), there is a reference checklist covering generic and railway specific factors, which is non-exhaustive, supporting the process of deriving influencing factors for the railway duty holder. Several aspects are listed, as following:

- System definiation and system design
- Operating conditions
- Application conditions
- Maintenance conditions

2.2.3. Human factors

Human factors are a core aspect within an integrated RAMS management process, which can be defined as the impact of human characteristics, expectations and behavior upon a system. Linked with Section 2.2.1, human influence can potentially result in both random and systematic failures depending on human involvement in certain phase of life cycle of system.

2.3. Specification of railway RAMS requirements

Specification of proper RAMS requirements is of utmost importance given the main goal of RAMS activities is to achieve a system performance meeting certain RAMS requirement. The specification of RAMS requirements is a complex process. Typical parameters and symbols are recommended in EN 50126. A whole picture of standards relevant to railway signaling system and their relationships has been concepted in Figure 2. EN 50129 (2018) is applicable to the functional safety of systems, subsystems or equipment which have been specified designed and manufactured for railway signaling applications.

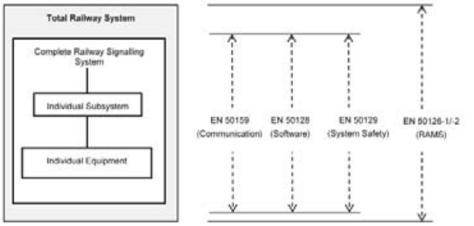


Figure 2 Scope of the main CENELEC railway application standards

3.Railway Signaling system

3.1. Brief introduction

Railway signaling system is used to ensure the safe operation of the railway, which is located on the side of railway line to give information of the state of railway line ahead to the train divers. The main purpose of the railway signaling system is fulfilled by the combination of the functionalities of several parts, e.g. signals, level crossings, Interlocking system and so on. Figure 3 shows the main systems(Tang 2015). And each part has its own particular goal and can be considered a complex system on its own.

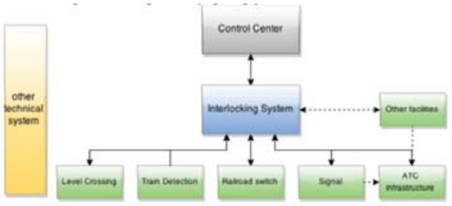


Figure 3 Norwegian railway signaling system

3.2. Multi-layer structure

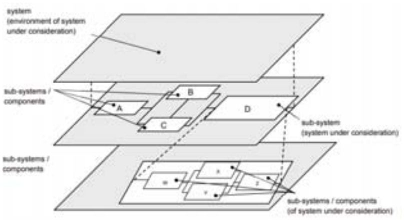


Figure 4 System structure and hierarchy

As described in Section 3.1, railway signal systems are large complex systems made of multiple hierarchical layers with a long-expected life (in general, between 30 and 40 years)(Estevan 2015). The multiple hierarchical layers structure rises the new challenges in the performance evaluation with the involvement of many stakeholders, e.g. the manufacturer, operator and the maintain crew etc. Meanwhile, operating and maintenance condition can affect greatly the operating performance of the signal systems as well.

Also, given the execution of several systems to achieve the final purpose, which is to ensure the safe operation of railway, the neglection of dependences among systems will not give a full picture of the whole system. In a signal system, different failures can lead to the same failure consequence, in terms of the effects of transportation, which challenges the identification of the real contributor. Furthermore, the complex structure of electronics and the interdependency of components and systems make it difficult to identify and analyze anomalous behaviors (Dorj, Chen, and Pecht 2013). Therefore, the railway system can be considered as a system of systems (SOS)(Estevan 2015).

3.3. Performance requirements

The ultimate task for railway signaling system is to provide control, supervision and protection of safe operation for railway. Therefore, the performance requirement is determined by the allocated safety target after the systematic risk assessment. EN 50129 (2018) provides a hazard analysis process to guide the apportionment of hazardous failure rates to potential safety functions, as shown in Figure 5.

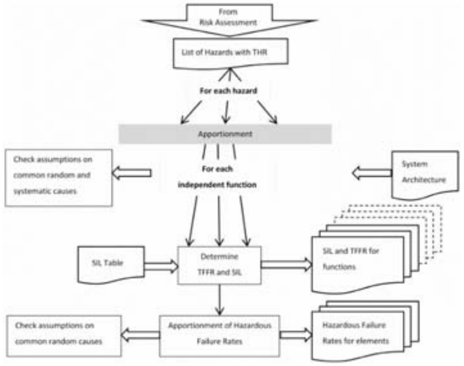


Figure 5 Example of a hazard analysis process

4.Functional safety and performance requirement

Safety integrity related to the ability of a safety-related system to achieve its required safety functions. The higher the safety integrity, the lower the likelihood that it will fail to carry out the required safety functions. A safety integrity level (SIL) is a way to indicate the tolerable hazard rate (THR) or a hazard rate of a particular safety-critical function. A safety critical system may have many safety-critical functions with different SILs. Following the safety integrity requirements, each safety function should be specified in terms of the safety integrity level (SIL) considering the operation mode(IEC 61508 2010).

Table 1 SIL table (IEC 61508 2010)

SIL	Average probability of a dangerous failure on demand (PFDavg)	Average frequency of a dangerous failure per hour
4	10^{-5} to 10^{-4}	10^{-9} to 10^{-8}
3	10^{-4} to 10^{-3}	10^{-8} to 10^{-7}
2	10^{-3} to 10^{-2}	10^{-7} to 10^{-6}
1	10^{-2} to 10^{-1}	10^{-6} to 10^{-5}

Different with IEC 61508, EN 50129 defines SIL by the THR,

Table 2 SIL table with THR (EN 50126 2017)

SIL	THR (per hour)
4	10^{-9} to 10^{-8}
3	10^{-8} to 10^{-7}
2	10^{-7} to 10^{-6}
1	10^{-6} to 10^{-5}

The related equations of PFH and THR are summarized in (Beugin, Renaux, and Cauffriez 2007).

Table 3 Quantitative indicators for the high-demand mode

	Related equations
PFH	Sum of the dangerous failure rates for all the subsystems serving a safety function $\mathrm{PFH(T)} = \frac{1}{T} \cdot \int_0^T \omega(t)dt$
THR	THR= $\lambda_{DD} + \lambda_{DU}$ Hazard rate for functions and subsystems, D: dangerous hazard, DD: detected dangerous hazard, DU: undetected dangerous hazard

The THR associate to a safety-critical function (SCF) coincides with the PFH of the entire system implementing the SCF, THR = $\mathrm{PFH}_{\text{entire system}}$(Tang 2015). Here, the SCF can be allocated to different subsystems, such as:

- The interlocking system shall set correct output signals/send correct data the controlled objects, given correct input signals/data into the interlocking system;
- Railroad switch will lock switches and give the correct information about position and locking status to the interlocking system;
- Train detection shall detect an unoccupied railway section and give correct information about whether a railway section is occupied or not to the interlocking system.

5.Reliability modeling and analysis methods

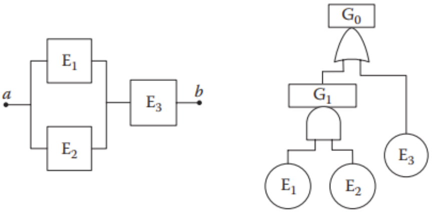
Y. Wang et al. (2020) discussed the different definition of redundant structure in EN 50129 (2018) and IEC 61508 (2010) and drew a conclusion that the 2oo2 structure in EN 50129 (2018) is equivalent to the 1oo2 configuration defined in IEC 61508 (2010) series standard. Therefore, the existing techniques for evaluating probabilities of hardware failure in IEC 61508 (2010) should also be applicable for the performance analysis of railway signaling systems. In this section, several common-used RAMS methods will be presented here.

5.1. Boolean approach –RBD and FT

The Boolean approach encompasses the techniques representing the logic function linking the individual component failure to the overall system failures. The main Boolean models are Reliability Block Diagram (RBD), Fault Tree (FT) and so on.

RBD is success-oriented network with two basic events including functional blocks (rectangles) and the connections (lines) between blocks, as shown in Figure 6(a). The RBD has two basic structures: series structure and parallel structure. In a series structure, the system is functioning if and only if all of its *n* components are functioning, while in the parallel structure, the system is functioning if at least one of its *n* components is functioning. IEC 61508 (2010) treats sensor subsystem, logic subsystem and the final element subsystem as in the series structure, while the redundant structure of each subsystem can be simplified as parallel structure. This graphical representation is easier to visualize the physical structure and provide a good support for engineers to discuss.

While FT has exactly the same properties as RBD is based on a top-down logic diagram with a tree shape as shown in Figure 6(b). The analysis generally starts from defining the TOP event or the system failure of interest, and the next step is to identify the direct causes of the TOP event and connect them logic gates (One is the OR gate, and the other is the AND gate).



(a) (b)

Figure 6 Simple example of an RBD and FT

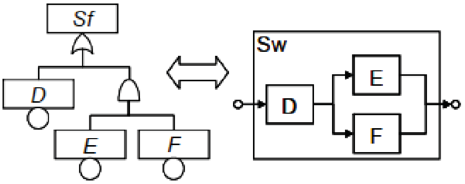


Figure 7 Equivalence FT/RBD

RBD and FT representing exactly the same things, the calculations may be handled exactly in the same way. Figure 7 shows small equivalent FT and RBD. To apply the Boolean approach to an SCF. It would start from the establishment of a FT targeting a specific SCF with TOP event 'The SCF has a D failure', and then to identify the combinations of basic events in the FT, including both individual faults and Common Cause Failures (CCFs). To get a dangerous SCF failure, the importance of a basic event *i* should be classified and quantified at time *t* by Birnbaum's measure of importance $I^B(i|t)$. Then the frequency of the occurrence of the TOP event at time *t*, caused by the independent basic event *i*, is therefore

$$\omega_{\mathrm{TOP},i}(t) = I^B(i|t)\omega_i(t) \qquad (1)$$

where $\omega_i(t)$ is the unconditional rate of occurrences of basic event *i* at time *t*. Therefore, the instantaneous $\mathrm{PFH_G}(t)$ related to the specified SCF is

$$\mathrm{PFH_G}(t) = \sum_{i=1}^{n} I^B(i|t)\omega_i(t) \qquad (2)$$

where *n* is the number of basic events in the FT.

Here, we can take the example in Figure 7 as an explicit modeling for 1oo2 system (unit E and F) with CCF(modeled as unit D in Figure 7). Then, the importance of basic event *i* can be calculated as

$$\begin{aligned} I^B(D|t) &= p_E(t) + p_F(t) - p_E(t)p_F(t) \\ I^B(E|t) &= p_D(t)(1 - p_F(t)) \qquad (3) \\ I^B(F|t) &= p_D(t)(1 - p_E(t)) \end{aligned}$$

For the rate of occurrence of failures (ROCOF) $\omega_i(t)$ can be estimated as the failure rate λ (for not too large values of *t*). Further, we can estimate the $\mathrm{PFH_G}(t)$ in Eq (2).

In terms of performance evaluation, RBD is also mentioned in EN 50129 (2018). Flammini et al. (2006) have evaluated system reliability of European Train Control System (ETCS) by fault trees, in consideration of the modeling capability of FTA for large-scale systems. Song and Schnieder (2018) combined a method to represent and extend the fault tree in the Colored Petri nets, taking the advantage of the dependability analysis, for the train movement authority plus system to reduce the risk of train head to tail collisions. Jiang, Wang, and Liu (2018) employed the FTA analysis where the basic events are divided into known failure rate and unknown failure rate to evaluate the reliability of the Chinese train control system level 3 (CTCS-3), which comprising an onboard and trackside subsystem.

5.3. Markov Method

Both the FTA and RBD methods are very effective tool in the structural reliability analysis of systems, but it is difficult for them to analyze some dynamic behaviors of systems, such as maintenances and restorations form faulty states. Some state transition models are therefore introduced in the system analysis, and one of the most widely used is the Markov method.

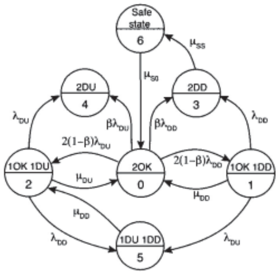


Figure 8 Markov model for the 1oo2 voted system

A diagram is normally used to illustrate the transitions between different system states. Figure 8 shows a Markov diagram for a 1oo2 system, where the circles represent the potential system states and transitions, as detailly described in Table 4.

Table 4 The possible states for the 1oo2 voted system

State	State description
0	Both OK
1	One DD fault, one is OK
2	One DU fault, one is OK
3	Both DD faults
4	Both DU faults
5	One DD fault the other a DU fault
6	The EUC is brought to a safe state

The voted system is functioning in the state $\mu = \{0,1,2\}$ and is failed in the state $\Theta = \{3,4,5\}$. The following transitions will give a dangerous failure of the voted system: 0→4, 1→5, 2→4 and 2→5. The instantaneous $\mathrm{PFH}_G(t)$ at time t is therefore

$$\begin{aligned}\mathrm{PFH_G}(t) = \; & P_0(t)\beta\lambda_{DU} + P_1(t)\lambda_{DU} \\ & + P_2(t)(\lambda_{DU} + \lambda_{DD})\end{aligned} \tag{4}$$

A detailed description of Markov methods for the performance assessment of safety-critical systems can be found in Rausand (2014). In addition, cases of reliability analysis for system-critical systems (Liu and Rausand 2011, 2013; A. Zhang et al. 2021) and railway applications can be found in many literatures(Morant et al. 2017; H. Wang et al. 2014).

Dersin and Blas (2016) employed the continuous time Markov chain to derive the system safety state probability and the transition rate to the unsafe state to address the unnecessity of assumption for the instant restoration of the system to its nominal state once it has reach the safe state following the triggering of the barrier.

5.4. Petri Net

Another recommended method in IEC 61508 (2010) for performance analysis of safety critical systems with state transition is the Petri net, which is a graphical tool with better performance in terms of modeling flexibility. A Petri net generally consists of two static elements, including places and transitions, which are connected by arcs. Tokens, residing in the place and regarded as a system state, are dynamic elements which represent the movable resources in the system.

Petri Net describes discrete dynamic systems which is isomorphic to continuous time Markov Chain, which is easily used for modeling of discrete dynamic system, performance and reliability analysis. Petri Net has been used for railway signal systems modeling based on optical fiber communication system(Chen and Sun 2012), considering the dual module hot spare for the signal devices subsystems and parallel redundancy for the routing equipment subsystem.

Considering voting structure in railway signaling system, such as computerized interlocking system, Guo, Huang, and Liu (2006) discussed and evaluated the performance of system with a structure of 2 times 2 voting system based on High level Petri net, which verified the benefits of using Petri net in performance modeling and analysis of railway signal systems.

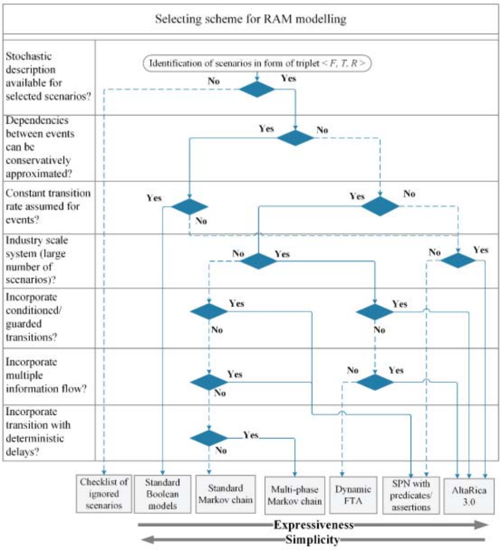


Figure 9 A formalized guideline on selecting RAMS modeling methods

A systematical selection guideline for the RAMS methods is presented in (J. Zhang 2018). For RAM modelling, the spectrum of events can be given as a set of triplets, <*F*, *T*, *R*> and F denotes the failure events, which is assumed to be stochastic process. T denotes the event to confirm the state in response to F, which can be continuous monitoring or periodic test. R denotes the event the brings the system from the abnormal state back to the normal state (e.g. repair and maintenance) or other functioning state (e.g. switch to standby or degraded state). A formalized guideline to choose the evaluation methods has been discussed and presented (J. Zhang 2018) and attached in Figure 9.

6.Conclusion

Railway signaling systems are one of safety critical systems which calls for more attention in the performance assessment. This paper has reviewed several international standard related to functional safety of safety-related systems, e.g. EN 50126 (2017); EN 50129 (2018); IEC 61508 (2010). Given the complex structure and functions of subsystems, railway signaling system can be regarded as system of systems, which could be an interesting but challenging research topic. A comparison of different indicators, THR and PFH in terms of safety functions, has been summarized based on different international standards. Also, this paper has reviewed several commonly used modeling approaches for safety related system and presented their application in performance analysis of the railway signaling systems, which provided some preliminary clues for engineers and analysts.

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