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Introduction

The topic of fire safety in rolling stock has a relatively short history compared to other railway areas. Awareness of fire risk appeared in the 1970s along with the increase in popularity of railways, which became a mass means of transport, as well as with the proliferation of plastics in vehicle equipment. The increasing number of fires in passenger rolling stock from year to year led to the search for tools for their assessment and then methods for their prevention. Currently, issues related to fire protection of passenger rolling stock constitute an extensive and increasingly rapidly developing field. For example, the Polish standard PN-84/K-02500 *Rolling stock — Fire safety of materials — Requirements* [3], established in 1984, was one of the first to address this problem.

Yet, the greatest progress has been made in developing fire testing methods and product classification, which is still being developed. Research centres of individual European railways, much like those outside Europe, have developed different test methods and rules for assessing and authorising products for use.

The diversity of research methods and the principles of classifying and approving materials for use in the absence of comparative tests, making it impossible to determine correlations between them, as well as the occurring fires, made researchers aware of the constant imperfection of the developed systems. Moreover, different requirements applicable in individual countries forced suppliers to conduct separate tests for individual recipients.

The first actions taken to standardise test methods and requirements in the wake of the development of UIC Code 564-2 [4] did not bring the expected effect. The legislative process concerning the European standard EN 45545 [2] took a long time nonetheless [1]. The delays in this standardisation work resulted, on the one hand, from an attempt to keep up with the adaptation of research methods to new materials, e.g. thermoplastic materials, and on the other, from the continuously increasing knowledge on the phenomena occurring during the spread of fire in a moving vehicle. At the same time, it should be remembered that research methods always, to a greater or lesser extent, represent simplified operating conditions, including in terms of the economic aspect (small samples). Nonetheless, laboratory tests in repeatable conditions make it possible to learn how materials react to various ignition sources, as well as to compare their properties and classify products. It should also be emphasised that new requirements regarding fire properties have become an incentive to modify technological processes, taking into account the use of flame retardants and other innovative solutions.

Still, the general assumption of fire protection measures for rail vehicles is to protect passengers and crew in the event of a fire on board by reducing the risk of fire, delaying the development of fire, controlling the spread of its products, as well as ensuring appropriate evacuation conditions. The above objectives are achieved using passive and active protection measures. Passive measures include requirements concerning such areas as:

- fire properties of materials and elements as well as fire barriers,
- preventing fire due to leakage of flammable liquids or gases,
- reducing the risk of fire both during operation and as a result of technical damage and/or malfunction of electrical equipment,
- uninterrupted operation of emergency electrical equipment until the evacuation is completed.

In contrast, active protection includes rail vehicle on-board fire protection systems for detecting fire, warning about it and extinguishing it.

A related area is the technical specification requirements for interoperability and certification of rail vehicles and their components. The assessment of risk in the field of fire safety of rail vehicles is, however, a relatively new issue.

Progress in rolling stock fire protection is also based on a detailed analysis of actual past events and those simulated as part of rescue and fire-fighting exercises, as well as the implementation of conclusions formulated on their basis.

At the same time, a new hazard arises along with the growing interest in using alternative fuels to power rail vehicles and transporting such cargo, requiring the development of European regulations in this area.

This five-chapter monograph is a review of the current standardisation and legal regulations, as well as research and development achievements in the increasingly expanding field of rolling stock fire protection. Most of the chapters were written by the authors of papers presented at the 5th International Conference "Modern Directions in Fire Protection of Rolling Stock", held by the Railway Research Institute in Warsaw on 10–11 May 2022. However, to obtain a more complete picture of some of the presented areas, this study also includes additional chapters prepared by recognised Experts.

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[2] EN 45545, Parts 1 to 7 — Railway Applications. Fire Protection on Railway Vehicles.
[3] PN-84/K-02500 — Rolling Stock — Fire Safety of Materials — Requirements.
[4] UIC Code 564-2: Regulations Relating to Fire Protection and Firefighting Measures in Passenger Carrying Railway Vehicles or Assimilated Vehicles Used on International Services.

1 European and National Standardisation in Rolling Stock Fire Safety

The treaty signed on 7 February 1992 in Maastricht, which entered into force on 1 November 1993 (after referenda held in twelve member states), established the European Union. Its main goals were to ensure economic stability, security, defence and environmental protection of the member states, of which there are currently 27. The above is related to simplifying and adapting the legal framework to reflect the latest and future developments and poses a major challenge, including in terms of European standardisation. The harmonisation of requirements contributes to increasing and strengthening market competition, reducing costs and improving safety while protecting health and the environment. European standardisation is an integral part of supporting global competitiveness and a driving force for economic growth, building consumer confidence and innovation. It aims to focus on consolidating and strengthening the European single market. Another vital challenge is continuing to remove technical barriers to trade and supporting economic growth, including by identifying environmental trends and social expectations. At the same time, European and international standards should serve to assess compliance, with the right to market access as a reference point for this assessment [3].

Per CEN/CENELEC internal regulations, CEN CENELEC members are obliged to give a European Standard the status of a national standard without introducing any changes while simultaneously withdrawing any conflicting national standards.

However, the unification of research methods and evaluation criteria across various areas is progressing at different rates. This is due to a diverse range of historical and technical conditions. This also applies to rail transport fire safety. As already mentioned in the introduction to this monograph, different countries have developed their own research methods and rules for assessing products and authorising their use. This was due to the diverse ways in which rolling stock developed around the world, as well as the divergent rules for the use and maintenance of vehicles in individual countries. This also means that the causes of the fires varied. The process of developing the EN 45545 [1] series of standards was thus one of the longest in the history of European standardisation and required verification shortly after its completion. The first subchapter of this chapter presents the current status of verification of the EN 45545 [1] series of standards and the process of their migration to ISO standards. The progress of work on the development of the FCCS standard is also discussed, as is the updated schedule and scope of further stages of verification and full implementation of EN 45545 [1]. Further, the approach to projects that have already started and tests carried out in accordance with EN 45545-2: 2013 + A1: 2015 [2] is explained.

Notably, European Standardisation does not exclude the use of national standards insofar as they do not conflict with European standards. The next subchapter presents the role of the Rail Safety and Standards Board (RSSB) and the Rail Accident Investigation Branch (RAIB) established in the United Kingdom, with particular emphasis on fire safety.

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[1] EN 45545 Parts 1 to 7 — Railway Applications. Fire Protection on Railway Vehicles.

[2] EN 45545-2: 2013 + A1: 2015 — Railway Applications. Fire Protection on Railway Vehicles. Part 2: Requirements for Fire Behaviour of Materials and Components.

Websites

[3] https://www.cen.eu/cen/pages/default.aspx — Strategic Objectives for the European Standardisation System to 2020 — Draft for public consultation_2013.03.12.

1.1. Revision and advancement of the EN 45545 Series of Standards and Related Standards

The EN 45545 series of standards — *Railway Applications. Fire Protection of Railway Vehicles* — includes fire protection measures and requirements aimed at minimising the likelihood of fire and controlling the speed and extent of its spread. The primary goal is to minimise the impact of possible products of fire on the passengers and crew.

An important tool for assessing fire risk is the criteria for selecting rail vehicle construction and equipment materials in terms of their fire properties. This was the very area that was the most difficult to agree upon during the European standardisation process to create the EN 45545 [11–17] series of standards, effectively extending this process to 22 years. The focus of the CEN/CENELEC TC256 JWG working group shifted many times due to an ever-changing approach to research and requirements. However, the European Commission gave high priority to this standardisation work and the EN 45545 [11–17] series of standards was eventually established in March 2013. Moreover, in April of that year, CEN's WG01 TC256 working group was re-established to verify and refine the standards in question. This resulted from the recent advances in knowledge and experience on the phenomena occurring during the spread of fire in a moving vehicle, as well as from the marketing of new materials (e.g. from the category of thermoplastics) whose behaviour during certain tests made it impossible to clearly determine the parameter being tested and qualify the product [11–17].

1.1.1. Directions/Assumptions for Verifying the EN 45545 Series of Standards

The verification process assumed the implementation of the following actions by the end of 2019:

- verification of EN 45545 Parts 1 to 7,
- development of a new standard for fire testing of passenger seats,
- development of a new standard for smoke and toxicity tests,
- development of a new standard for Fire Containment and Control Systems (FCCS).

Figures 1.1.1. and 1.1.2 present the planned scope and schedule of verification.

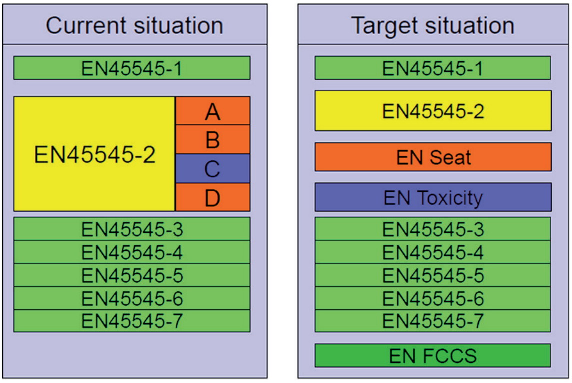

Figure 1.1.1. CEN TC256 WG1 work schedule of 1 April 2013 [2]

However, the adopted schedule was too optimistic and completing the assumed actions within the planned time proved impossible. Among other things, this was because some areas turned out to be more labour-intensive than expected. The Covid-19 pandemic caused additional delays as well.

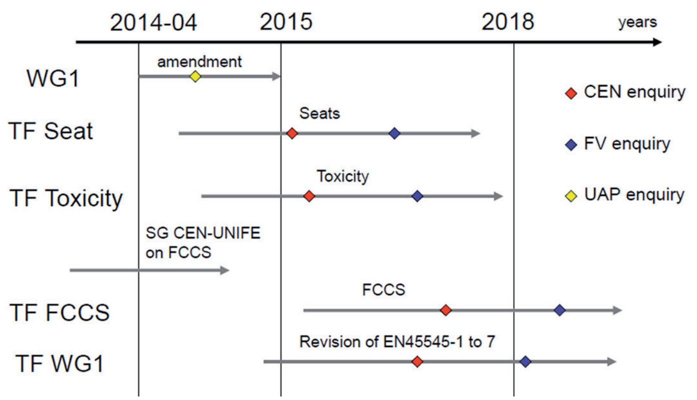

Figure 1.1.2. CEN TC256 WG1 work schedule of 1 April 2013 [2]

1.1.2. Progress of EN 45545 Revision

Below is the scope of work completed as of 29 February 2024 as well as further plans.

Revision of EN 45545-1 — *Railway Applications. Fire Protection on Railway Vehicles — General* [11]
This standard covers the following:

- basic definitions,
- operational categories,
- design categories,
- fire safety goals,
- general requirements for fire protection measures and assessment of their compliance.

The verification of the EN 45545-1 [11] standard has been transferred to the ISO level, where it is being developed as ISO 9828-1 by the ISO/TC 269 committee. On 23 September 2023, the document was registered as DIS, recognised as a standard contributing to achieving the Sustainable Development Goal. The publication of the ISO 9828-1 standard is scheduled for December 2024.

Revision of EN 45545-2 — *Railway Applications. Fire Protection on Railway Vehicles — Requirements for Fire Behaviour of Materials and Components*
The revision of the EN 45545-2 [12] standard is planned to take place in several stages. The first one introduced the changes described below in the EN 45545-2:2020 edition:

a. Adapted new research standards:
  - Deleted the following Annexes:
    - A (normative) Standard testing of seat covers,
    - B (normative) Seat fire test method,
    - C (normative) Test methods used to determine the toxicity of gases emitted from railway products during combustion;
  - Introduced the following new standards:
    - EN 16989 — *Railway Applications — Fire Protection on Railway Vehicles — Fire Behaviour Test for a Complete Seat* [9], replacing the existing Annexes A and B,
    - EN 17084 — *Railway applications — Fire Protection on Rail Vehicles — Toxicity Test of Materials and Components* [10], replacing the existing Annex C,
    - EN 60695-1-40 — *Guidelines for the Assessment of Fire Hazard of Electrical Products - Electrical Insulating Liquids* [19] in Table 6 for item T08 instead of EN ISO 2592 *Petroleum Products and Similar Products — Determination of Flash and Burning Temperature — Cleveland Open Cup Method* [20] and EN ISO 2719 *Determination of Flash Point — Pensky-Martens Closed Cup Method* [21];
  - Discontinued unrelated standards.

b. Added new terms and definitions.

c. Introduced several substantive changes resulting from previous experience in the following areas:
  - explained general rules for all products (4.2),
  - modified grouping rules, including the block diagram (4.3),
  - added two additional requirements R27 (for Ex13) and R28 (for composite products according to section 5.3.1.2),
  - changed requirements for several products (including seats);

d. Introduced new Annex B (informative) *Product Classification Guidelines*.

e. Editorial changes.

However, further work resulted in the development of EN 45545-2:2020+A1:2023. The scope of changes compared to the EN 45545-2:2020 edition is as follows:

a. Introduced the following remarks in the European Foreword:
  - The standard is to be given the status of a national standard without any changes no later than April 2024 and any conflicting national standards must be withdrawn no later than October 2026;
  - The purpose of the extended transition period is, on the one hand, to allow the industry to adapt to the new requirements and, on the other, to enable the use of certificates that are still valid under the previous version;

- Note on the inclusion of amendment A1, accepted by CEN on 23 July 2023.

b. Annex ZA (informative*) Relationship Between this European Standard and the Essential Requirements of Directive (EU) 2016/797* to be deleted.

The implementation of the second stage of the revision is planned for 2024–2028. Subsequently, work is planned to be carried out as part of the migration to ISO standards and the establishment of the ISO 9828-2 standard in late 2031.

Revision of EN 45545-3 — *Railway Applications. Fire Protection on Railway Vehicles — Fire Resistance Requirements for the Barriers* [13]

The year 2023 saw the release of the last developed version of prEN 45545-3:2023, a formal vote on which was held in August-September 2023.

The new version introduces the following main changes compared to the previous version of EN 45545-3:2013 [13]:

a. Modified the scope of the standard to add that using a Fire Containment and Control System as an alternative to a fire barrier, where permitted, is outside the scope of the standard;
b. Updated old references;
c. Renumbered section 5.1 due to the removal of the definitions of tightness (E), insulation (I) and radiation (W) criteria (previously 5.1.1, 5.1.2, 5.1.3 and 5.1.4) due to the referenced EN 13501-2:2016 [8];
d. Amended section 5.5, which introduced a changed reference to Drawings with examples of fire barriers, transferred to the new Annex B;
e. Amended the entries in Table 1 Requirements for fire barriers — additional consideration of lithium-ion batteries and the area on the roof of the vehicle;
f. Amended section 5.6.3 — the minimum opening dimensions for small heaters have been removed;
g. Amended section 5.6.4 — the entries in Table 2 have been verified and a note explaining its use has been added;
h. Amended Annex A (normative) Requirements for assembly and fastening of test specimens:
   - A.5 — the minimum opening dimensions for small heaters have been removed;
   - A.10 — a procedure has been added for using intumescent seals;

i) Added Annex B (informative) Drawings relating to section 5, containing Figures 1–4 from the old section 5.5.2.

Further work is planned at the ISO level in the years 2024–2026, as is the establishment of the ISO 9828-3 standard. CEN TC 256 and ISO TC 269 agreed on the migration of EN 45545-3 [13] in late 2023/early 2024.

Revision of EN 45545-4 — *Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Railway Rolling Stock Design*

In 2023, a new version of EN 45545-4:2023 [14] was developed, with a formal vote on it taking place between September and November 2023.

The main changes compared to EN 45545-4:2013 [14] are as follows:

a. New requirements added in section 4.2.3 — expanded requirements for storing luggage inside passenger areas;
b. Deleted section 4.2.6 on displays and televisions (the requirements of EN 45545-2 [12] apply;
c. Expanded the general requirements regarding evacuation means in section 4.3.2.1 (referencing ISO 3864-1:2011 [22], among other resources);
d. Expanded the general requirements in section 4.3.3.1 by adding item e), requiring that no emergency exits be present in areas intended for bicycles, strollers, etc.;
e. Added section 4.3.5 Emergency signs, referencing ISO 3864-1:2011 [23];
f. Added section 4.3.6 Emergency lighting, referencing EN 13272-1:2019 [6] and EN 13272-2:2019 [7].

The standard was scheduled for publication in the first quarter of 2024, to be followed by work at the ISO level to establish ISO 9828-4 in 2027.

Revision of EN 45545-5 — *Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Electrical Equipment Including That of Trolley Buses, Track Guided Buses and Magnetic Levitation Vehicles* [15]

Due to the introduction of a provision on lithium-ion batteries into prEN 45545-3:2023, it is planned that the upcoming 2024–2026 revision of Part 5, WG01, will deal with hydrogen batteries, traction batteries and new technologies. Subsequently, in the years 2029–2031, work is planned to be carried out as part of the migration to the ISO level to establish ISO 9828-5.

Revision of EN 45545-6 — *Railway Applications. Fire Protection on Railway Vehicles. Fire Control and Management Systems*

A new version of prEN 45545-6:2022 was released in 2022, containing the following changes compared to EN 45545-6:2013 [16]:

a) in Table 1 Fire detection:
   - added area: “Lithium-ion batteries in the main auxiliary power supply”,
   - removed footnote c for categories S and DS;
b) amended section 5.3.1, referencing, in the scope of automatic alarm reactions, sections 5.4.1 to 5.4.4 and the definition of the alarm trigger time according to EN 50553:2013 [18];

c) clarified the requirements for remote alarms in section 5.3.3;
d) added new requirements in section 6.3.1: If fixed fire-fighting equipment is present, there is no need to install an additional fire extinguisher in the area protected by such equipment;
e) added new requirements in section 6.3.3;
f) deleted paragraph 8.

Formal voting has been postponed by CCMC and will be held in 2024, with publication to follow in late 2024.

Subsequently, between 2027 and 2029, work is planned to be carried out as part of the migration to the ISO level to establish ISO 9828-6.

Revision of EN 45545-7 — *Railway Applications. Fire Protection on Railway Vehicles.* Fire *Safety Requirements for Flammable Liquid and Flammable Gas Installations* [17]

Due to the introduction of a provision on lithium-ion batteries into prEN 45545-3:2023, it is planned that the upcoming revision of Part 7, WG01, will deal with hydrogen batteries, traction batteries and new technologies. Then, migration to the ISO level is planned between 2029 and 2031 to establish ISO 9828-7.

Progress of Work on prEN FCCS

The work of WG01 ended with the development of the TP CEN/TR 17532:2020 (FCCS) Technical Report — *Railway Applications. Fire Protection on Railway Vehicles. Fire Control and Containment Systems* [23].

The document defines the FCCS assessment and related fire detection systems in rail vehicles as an alternative to fire barriers set out in Part 3 of EN 45545.

The TR FCCS describes the following:

- a method for assessing the installation and capabilities of the fire detection system,
- an assessment of the interaction of the fire detection system with FCCS, including the use of a vehicle mock-up or a real-scale test.

Additionally, new units are required to meet the requirements of EN 45545-2 [12] (fire properties) and EN 45545-4[14] (design principles) to comply with the safety requirements of EN 45545.

Subsequently, this TR is planned to be supplemented and improved to develop the EN standard. This, however, requires appropriate research.

Considering the above, work on the development of EN FCCS has been excluded from the EN 45545 series [11–17].

1.1.3. Other Standardisation Work in the Field of Railway Rolling Stock Fire Protection

Due to the connections between fire safety and other rail vehicle functional requirements, this topic was also taken up by the TC9X working groups. The progress of their work is described below:

- TC9X SG29: "Guide to the use of EN 45545-2 and EN 45545-5 for electronic equipment on board of rolling stock". Group convenor: Mr Carlo Fasoli. Work in progress. The technical report has not been published yet.
- TC9X SG31: "Guidelines for the use of EN 45545-2 for NiCd batteries on board rolling stock", Group convenor: Mr Pierre Prenleloup. Technical Report: TR 50718 [24] has been published, some elements of which will be incorporated into EN 45545-2 as part of the second revision. The scope of this document is to guide users of the EN 45545 series, particularly EN 45545 2:2013+A1:2015 and EN 45545 5:2013+A1:2015, in applying these standards when designing and assessing NiCd batteries on board trains, in terms of protective measures and fire protection. The document does not establish new requirements, only taking into account the requirements specified in the above standards. However, since EN 45545 is a general requirement and does not specifically address NiCd batteries, this guide is helpful when using these batteries.
- TC9X SG35: "Revision of EN 50553", Group convenor: Mr Guillaume Craveur. The work of this WG was scheduled to start in March 2024.

1.1.4. Fire Safety Requirements in the LOC&PAS TSI

The LOC&PAS TSI [4] was amended in 2023. The fire safety requirements contained in section 4.2.10 refer to the standards in Appendix J, as presented in the table 1.1.1. Unfortunately, as one can see, there are no references to the current edition of EN 45545-2 [12].

Compared to the 2019 edition, the 2023 LOC&PAS TSI [4] introduced the following significant change in section 4.2.10.2.1.

In order to ensure constant product characteristics and manufacturing process, it is required that:

- the test reports to prove compliance of a material with the standard, which shall be issued immediately after testing of this material, shall be renewed every 5 years,
- in case there is no change in the product characteristics and manufacturing process, and no change in the related requirements (TSI), it is not required to perform new testing of this material; expired test reports shall be accepted provided they are accompanied with a recent statement delivered at the placing on the market of the product from the original equipment manufacturer that there

has been no change in the product characteristics and in the manufacturing process, covering the complete supply chain involved, since the fire behaviour properties of the product were tested. These statements shall be delivered once the initial test report is expired, i.e. after 5 years.

Table 1.1.1. Standards referred to in the LOC&PAS TSI in Appendix J [4]

Index No.	TSI		Standards	
	Properties	Section	Document No.	Obligatory sections
58	Measures to prevent fire – material requirements	4.2.10.2.1	EN 45545-2:2013+A1:2015	Correct section [(1)]
59	Specific measures for flammable liquids	4.2.10.2.2	EN 45545-2:2013+A1:2015	Table 5
60	Fire spreading protection measures for passenger rolling stock – partition test	4.2.10.2.4	EN 1363-1:2012	Correct section [(1)]
61	Fire spreading protection measures for passenger rolling stock – partition test	4.2.10.2.5	EN 1363-1:2012	Correct section [(1)]
63	Running capability	4.2.10.24.4	EN 50553:2012 and EN 50553:2012/AC:2013	Correct section [(1)]

[(1)] Sections of a given standard that are directly related to the requirement specified in the TSI section given in column 3.

1.1.5. Conclusions

- The time set by CEN and accepted by WG01 for verifying the series of standards by 2018 turned out to be too short. However, the verified standard must be accepted and understood by all stakeholders (designers, manufacturers, users, researchers and certification bodies).
- It should also be emphasised that the European Railway Agency plays an important role in achieving consistency between the changing EN 45545 [11–17] standards and the provisions in the LOC&PAS TSI [4].

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[5] EN 1363-1:2012 Fire Resistance Tests — Part 1: General Requirements.

[6] EN 13272-1:2019 Railway Applications — Electrical Lighting for Rolling Stock in Public Transport Systems — Part 1: Heavy Rail.

[7] EN 13272-2:2019 Railway applications — Electrical Lighting for Rolling Stock in Public Transport Systems — Part 2: Urban Rail.

[8] EN 13501-2:2016 Fire Classification of Construction Products, Building Elements. Classification Using Test Data From Reaction to Fire Tests.

[9] EN 16989 Railway Applications — Fire Protection on Railway Vehicles — Fire Behaviour Test for a Complete Seat.

[10] EN 16989 Railway Applications — Fire Protection on Railway Vehicles — Fire Behaviour Test for a Complete Seat.

[11] EN 45545-1 Railway Applications. Fire Protection on Railway Vehicles. General.

[12] EN 45545-2 Railway Applications. Fire Protection on Railway Vehicles. Requirements for Fire Behaviour of Materials and Components.

[13] EN 45545-3 Railway Applications. Fire Protection on Rail Vehicles. Fire Protection on Railway Vehicles – Fire Resistance Requirements for the Barriers.

[14] EN 45545-4 Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Railway Rolling Stock Design.

[15] EN 45545-5 Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Electrical Equipment Including That of Trolley Buses, Track Guided Buses and Magnetic Levitation Vehicles.

[16] EN 45545-6 Railway Applications. Fire Protection on Railway Vehicles. Fire Control and Management Systems.

[17] EN 45545-7 Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Flammable Liquid and Flammable Gas Installations.

[18] EN 50553:2013 Railway Applications — Requirements for Running Capability in Case of Fire on Board of Rolling Stock.

[19] EN 60695-1-40 Guidelines for the Assessment of Fire Hazard of Electrical Products — Electrical Insulating Liquids.

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[21] EN ISO 2719 Determination of Flash Point — Pensky-Martens Closed Cup Method.

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[23] TP CEN/TR 17532:2020 (FCCS) Technical Report — Railway Applications. Fire Protection on Railway Vehicles. Fire Control and Containment Systems.

[24] TR 50718:2021 Guidelines for the Use of EN 45545-2 for Ni-Cd Batteries on Board Rolling Stock.

1.2. A New Standard for Rail Vehicle Fire Safety and Evacuation

Railway Group Standard GMRT2130 Issue Five and Rail Industry Standard RIS-2730-RST Issue One were published in June 2020. In accordance with GB legislation, GMRT2130 contains only National Rules; RIS-2730-RST sets out GB practice to control the risks of fire on rolling stock, including compliance with the EN 45545 series of standards, and GB practice for evacuation trials. Both documents supported compliance with the European Technical Specification for Interoperability (LOC&PAS TSI).

All RSSB standards include requirements (what must be done), which are now supported by rationale (why it must be done) and guidance (which may include suggestions as to how to meet the requirements). Most of the guidance in the new documents was previously provided in separate Guidance Notes or Codes of Practice.

All RSSB standards are reviewed 12 months after publication, and the UK left the EU at the end of 2020. The opportunity was taken to revise GMRT2130 and RIS-2730-RST to refer to the National Technical Specification Notice for Locomotives and Passenger Rolling stock (LOC&PAS NTSN), which substantially reproduces the TSI. Some other minor changes were made, due to the publication of EN 45545-2:2020, and to reflect feedback from industry. For evacuation assessments, RIS-2730-RST already included the possibility of using validated simulation models; it is understood that this will be permitted in the next revision of the TSI and NTSN.

GMRT2130 Issue 5.1 and RIS-2730-RST Issue 1.1 were published in September 2021 and are available on the RSSB website.

1.2.1. Background

On 5 October 1999, two passenger trains collided head-on in the Ladbroke Grove area of London, not far from Paddington station. Tragically, 31 people were killed and 417 injured. Lord Cullen's investigation report into this and the Southall crash (1997) [1, 2] led to the establishment of both the Rail Safety and Standards Board (RSSB) and the Rail Accident Investigation Branch (RAIB).

Amongst other things, RSSB is responsible for managing risk to railway employees, passengers and the public. As part of this, we manage standards on behalf of the GB rail industry, which includes representing the British Standards Institution (BSI) on the railway-related committees in CEN/CENELEC and ISO/IEC. All standards are written on a collaborative basis, with representation from and consultation with representatives from across the GB rail industry.

1.2.2. The Legislative Perspective. What is a Standard?

Put simply, a standard is an agreed way of doing things. According to BS EN 45020:2007 (ISO/IEC Guide 2:2004) [3], a standard is a *document, established by consensus and approved by a recognised body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context*. Standards may include requirements and/or recommendations in relation to products, systems, processes or services. Standards can also be used to describe a measurement or test method or to establish a common terminology within a specific sector. Some of the benefits of standards are illustrated in Figure 1.2.1.

Figure 1.2.1. The benefits of standards (source: author's own work)

Figure 1.2.2 shows the legislative situation in the UK before we left the EU; the post-Brexit regime is shown in Figure 1.2.3.

The Hierarchy of Legislation and Standards

Principally, legislation is clearly mandatory; this is supported by the NTSNs (formerly the TSIs), which are also mandatory. The NTSNs (and TSIs) also mandate certain clauses of several European standards (ENs) and some International Standards (ISOs). For the UK, Railway Group Standards (RGSs) are mandatory documents. Railway Industry Standards (RISs) are mandated by the Office of Rail and Road's Licensing conditions — unless the Licensee can demonstrate an alternative means of addressing the risk. In some cases, NTSNs, RGSs and RISs are supported by separate Guidance Notes and Codes of Practice.

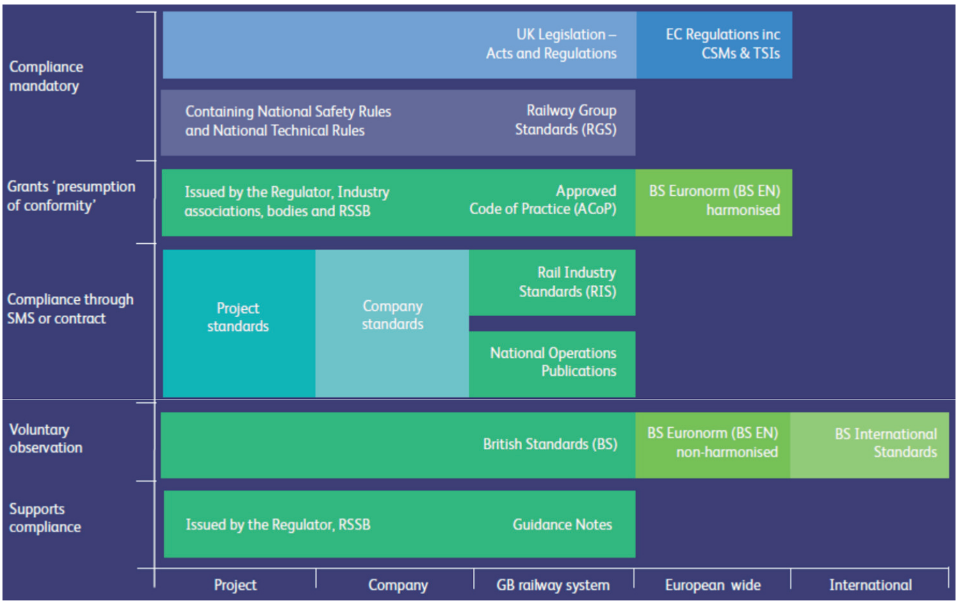

Figure 1.2.2. UK Legislation in 2020 (source: author's own work)

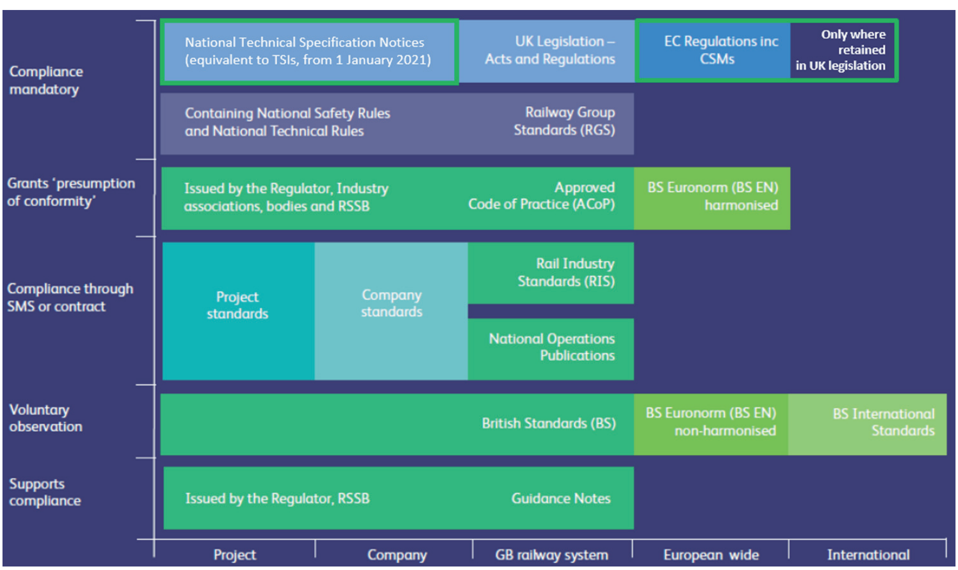

Figure 1.2.3. UK Legislation in 2021 (source: author's own work)

Although the LOC&PAS NTSN [4] calls up EN 45545-2:2013 [5], it also permitted the continued use of BS 6853 [6] and GMRT2130 Issue Three [7] in the UK until 1 January 2018. GMRT2130 was revised to Issue Four in 2013 [8] to align with the LOC&PAS TSI [9], and hence with EN 45545-2:2013. There was a small amendment in 2016 [10] to refer to clause 7.2.4 in the Safety in Rail Tunnels (SRT) TSI [11], which permits the running of new trains in existing tunnels greater than 5km in length.

GMRT2130 Issue Four was supported by the following Guidance Note and Codes of Practice:

- GMGN2630, Dec 2013 [12] — Guidance on Rail Vehicle Fire Safety.
- GMRC2531, June 2008 [13] — Emergency Lighting.
- GMRC2532, June 2008 [14] — Emergency and Safety Equipment.
- GMRC2533, June 2008 [15] — Communication of Emergency and Safety Information.
- GMRC2534, June 2008 [16] — Emergency Evacuation.

1.2.3. Emergency Evacuation

The TSI (and NTSN) requirement

Clause 4.2.10.5.1 (12) of the LOC&PAS TSI (NTSN) states:

> *The number of the doors and their dimensions shall allow the complete evacuation within three minutes by passengers without their baggage. It is permitted to consider that passengers with reduced mobility are to be assisted by other passengers or staff, and that wheelchair users are evacuated without their wheelchair.*
> *Verification of this requirement shall be made by a physical test under normal operating conditions.*

GB Experience of Evacuation Trials

A procedure for physical testing was developed in GB in direct response to the Ladbroke Grove accident; this was published as AVST9002 in December 2002 [17].

Key features of the evacuation test are:

- It is a fully risk-assessed activity, monitored by safety-trained professionals, with first aiders in attendance.
- The exercise is completed in the dark, with backup power (emergency lighting) active.
- Evacuation is conducted:
  - from the vehicle to the platform using side access; the platform is lit;
  - from the vehicle to an adjacent vehicle, using end access; and

  - from the vehicle to the track, without the deployment of any detrainment device.
- Each trial is done twice; financial incentives are used with the aim of improving evacuation time by 20%.
- The volunteers are aged between 16–65, with a number of infant manikins, and reflect a mix of business and leisure travellers. However, there are to be no groups comprising family or colleagues more than 6 persons, and approximately 40% of the volunteers are to be solo travellers.

This test procedure was moved to GMRC2534 in 2008. It is worth noting that GB standard practice is to evacuate a vehicle in 90 seconds, compared with the three minutes (180s) stated in the TSI and NTSN.

However, there have been some challenges in implementing this test procedure. For instance, it can be difficult to find sufficient volunteers. Agencies can be used, but they tend to impose charges, which increases the costs of the exercise. One instance used factory staff, but this goes against the maximum of 6 colleagues!

A number of questions have been asked by industry, for example:

- Is the use of financial incentives ethical? (It was established that this reflects the practice in the airline industry).
- Is the documented procedure actually practicable? (It is believed so, allowing for the challenges listed above).
- Could simulation be used in future? (As previously mentioned, the next revision of the TSI and NTSN will permit this, as already set out in the guidance in RIS-2730-RST [18]).
- What about persons with reduced mobility (PRMs)? RIS-2730-RST Issue 1.1 [19] includes the suggestion to use adult mannikins to represent a person needing to be carried (without a wheelchair) for evacuation.

1.2.4. The UK Position on Rolling Stock Fire Standards

Applicable Standards

GMRT2130 Issue Five [18] and RIS-2730-RST Issue One were published in June 2020. BS 6853 has been withdrawn, and reference is now made to EN 45545-2:2013 as set out in the NTSN (and TSI).

Passenger Seat Fire Safety and Research

However, the fire tests for passenger seats in EN 45545 were considered inadequate in GB. Essentially, a seat that passed the EN test may not meet the requirements of BS 6853, and the Office of Rail and Road (ORR) would not therefore permit an EN 45545-compliant passenger seat design to be used in the UK. RSSB Research Report T1018 (2014) [21] compared the performance of passenger seat designs against the criteria in BS 6853 and EN 45545-2:2013 and recommended some improvements.

A new passenger seat testing method was therefore developed by CEN/TC256/WG1 and published as EN 16989 in August 2018 [22]. However, this was not compatible with the acceptance criteria set out in EN 45545-2:2013. For various reasons, the publication of EN 45545-2 was delayed until August 2020 [23], and then included a transitional period to August 2023.

Hence, RIS-2730-RST issue one when published in June 2020 required passenger seat testing to EN 16989 using the pass/fail criteria set out in the draft prEN 45545-2:2018.

A further standard was also developed for assessing toxicity: EN 17084 was published in December 2018 [24], which is also called up in RIS-2730-RST.

Structure and Content of the New RGS and RIS

GMRT2130 Issue Five sets out the National Technical Rules for fire safety on rail vehicles, addresses TSI (NTSN) open points and points where the TSI (NTSN) is silent. All RSSB standards include **requirements** (what must be done), which are now supported by **rationale** (why it must be done) and **guidance** (which may include suggestions as to how to meet the requirements). Most of the guidance in the new documents was previously provided in separate Guidance Notes or Codes of Practice.

One example **requirement** is that for internal doors, clause 2.9.2 of RIS-2730-RST. The requirement states:

If internal sliding doors are fitted, they shall either:
a) slide open in opposing directions at each end of the passenger saloon; or
b) be bi-parting.

The **rationale** states:

This requirement supports clause 4.2.10.5.1 of the LOC & PAS TSI and clause 4.3.2.1 of BS EN 45545-4:2013, controlling the hazards associated with emergency egress, particularly when vehicles are partially or wholly overturned. The EN refers to hinged doors only; this requirement reflects GB historical practice.

This is supported by the following **guidance**:

Alternatively, a means of escape through the doors may be provided within the door opening which allows through egress in the event of the door becoming jammed.

There is a risk that, under accident conditions, bi-parting doors may become jammed and hinder escape, due to their narrow width. It is therefore good practice to ensure that, where bi-parting doors are used, the door mechanism allows for distortion of the floor without jamming.

The development of both GMRT2130 Issue Five and RIS-2730-RST Issue One was based on GMRT2130 Issue Four, its supporting Guidance Note (GMGN2630) and the associated Codes of Practice GMRC2531, GMRC2532, GMRC2533 and GMRC2534) as detailed in section 2.3 above.

Each requirement set out in GMRT2130 was assessed as to whether it:

- met the criteria of an NTR; if so, it was a candidate for retention in GMRT2130 issue five;
- was duplicated in the TSI or an EN; if so, it was removed, and then replaced with a reference to the appropriate document; and
- was a "good" requirement; that is, whether it was useful in addressing the overall risks associated with fire on a rail vehicle.

This process therefore encompassed both clause-by-clause (bottom-up) and overview (top-down) assessments.

GMRT2130 is only 16 pages; it includes three NTRs and a means of addressing an open point:

- There are two tunnels in the UK which are longer than 5km, and which do not have intermediate fire-fighting points. On the basis that new trains are designed to meet the requirements of the TSI (NTSN) and the EN 45545 suite of standards and will therefore be inherently safer than those designed when these tunnels were built, it is considered safe in principle to run new trains through these existing tunnels. Clause 7.2.4 (b) of the SRT TSI reflects this, subject to a risk assessment.
- A matrix of compatibility between vehicle categories and infrastructure categories forms the second NTR; this has been retained from GMRT2130 Issue Four.
- The third NTR relates to a point on which the TSI (NTSN) is silent. There is a historical requirement in GB to direct diesel engine exhausts away from overhead line equipment to avoid contamination; a diagram is provided to illustrate this.
- The open point is that of the assessment of Fire Containment and Control Systems (FCCS) where used instead of full cross-section (vertical) fire barriers, such as might apply for trains designed with "wide-open" (inter-vehicle) gangways. The requirements in eGMRT2130 Issue Five reflect historical GB practice in this area, for example considering the gangway floor as an extension of the vehicle floor in terms of its performance as a (horizontal) fire barrier.

RIS-2730-RST Issue One runs to 36 pages, and covers the following subjects:

- It refers to the full suite of current EN 45545 standards, including EN 16989, EN 17084 and prEN 45545-2:2018.
- Sources of ignition, in reference to EN 45545-4 [25] Annex A.
- Liquids and gases, in reference to EN 45545-7 [26], including guidance for alternative fuels and refrigerants.
- Emergency lighting, in reference to EN 13272-1:2019 [27] Annex C.
- Emergency and safety equipment, as GB practice is to provide equipment over and above the TSI requirements.
- Signs and labels, referring to various standards:
  - EN 14752 [28] (signs for to doorways)
  - EN 61310-1 [29] (signs for fire extinguishers)
  - EN ISO 7010 [30] (signs for flammable liquids)
  - EN 16584-2 [31] (signs for passengers with reduced mobility)
  - ISO 3864-1 [32], ISO 3864-3 [33] and ISO 9186-1 [34] (symbols)
- Evacuation, including sliding internal doors.
- Guidance covering:
  - Emergency stop and isolation devices (EN 45545-6:2013[35]).
  - Maintenance and servicing, supporting clause 4.2.11 of the LOC & PAS TSI and EN 45545-4 Annex A.
  - Fire extinguishers (EN 45545-6).
  - Cleaning.
- Appendixes covering:
  - Fixed fire protection systems.
  - Emergency equipment (GB specifications).
  - Evacuation trials.

1.2.5. Continued Compliance

NTSNs and TSIs

At the time of writing, GB intends to maintain the NTSNs in parallel with the TSIs, although there is the possibility of divergence in the future. RSSB is actively supporting the Department for Transport (DfT) in this regard. Despite having left the EU, GB remains active in CEN/CENELEC and ISO/IEC; as mentioned earlier, RSSB represents BSI on several railway committees, including CEN/TC256/WG1 (Fire protection).

CEN/TC256/WG1

WG1 comprises fire safety experts from across Europe, including suppliers, train operators and standardisation organisations; the convenorship and secretariat is

France. The group is currently working on the revision of the EN 45545 suite of standards. as described in subchapter 1.1 of this monograph.

1.2.6. Conclusions

All RSSB standards are reviewed 12 months after publication, and the UK left the EU at the end of 2020. The opportunity was taken to revise GMRT2130 and RIS-2730-RST to refer to the National Technical Specification Notice for Locomotives and Passenger Rolling stock (LOC&PAS NTSN), which substantially reproduces the TSI. Other changes included:

- The Safety in Rail Tunnels (SRT) NTSN does not contain the previously referenced clause 7.2.4(b) regarding the operation of new trains in existing tunnels; a new clause was added to GMRT2130 to reflect this.
- Reference to EN 45545-2:2020, instead of prEN 45545-2:2018, including for the assessment criteria for passenger seats.
- Permission to continue toxicity testing to EN 45545-2:2013+A1:2015, reflecting the transition period for EN 45545-2:2020.
- Reordering of the clauses referencing FCCS in the context of wide-open gangways.
- The option of including adult mannikins in evacuation trials to reflect the potential need for passengers with reduced mobility to be carried (without a wheelchair) during an evacuation.

GMRT2130 Issue 5.1 and RIS-2730-RST Issue 1.1 were published in September 2021 and are available on the RSSB website.

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2 Certification and Risk Assessment in Rail Vehicle Fire Safety

Certification of rail vehicles and their components, as well as risk assessment, constitute an important area in the field of fire safety of rail vehicles. Directive 2016/797 of 16 May 2016 on the interoperability of the rail system in the European Union indicates fire safety as one of the prerequisites of overall safety, which is one of the six essential requirements forming basics for railway interoperability. The essential requirements in Annex III of the Directive include the following:

> *The design of fixed installations and rolling stock and the choice of the materials used must be aimed at limiting the generation, propagation and effects of fire and smoke in the event of a fire.*

The first subchapter discusses the European Commission Regulation 402/2013 on the common safety method for risk evaluation and assessment (CSM RA regulation) as well as Reliability, Availability, Maintainability and Safety standards (RAMS standards). It presents three approaches to risk analysis, assessment and acceptance:

- codes of practice,
- reference systems,
- explicit risk estimations,

which can be quantitative or qualitative, and can be utilized for fire-related risk analysis, assessment and acceptance. Schemes and application examples are also presented.

The next subchapter discusses the process of assessment and certification of components, rolling stock subsystems and rolling stock itself in accordance with EN 45545 Parts 1 to 7 [2–7]. It covers the cases of assessment and certification in the EU-regulated as well as the private sector.

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2.1. Risk Assessment in Rail Vehicle Fire Safety — Legal and Standardisation Requirements

The first directive on railway interoperability was accepted by the EU Parliament in 1996. Although it was dedicated only to trans-European transport network high-speed railways, fire safety was already being considered at that time. The initial railway interoperability directive, dedicated to conventional railways, was accepted more than 20 years ago (in 2001) and also took fire safety into account. As such, railway experts have cooperated at the European level for over 20 years to establish well-defined, comprehensive rules for mutual acceptance of rolling stock fire safety.

The Railway Interoperability Directive (UE) 2016/797, currently applicable to the EU Member States [1], defines six essential requirements: safety, reliability and availability, health, environmental protection, technical compatibility and accessibility, which are shortly defined in Annex III of the Directive in relation to the entire railway system as well as individual subsystems e.g. in relation to rolling stock. Appropriate fire safety is an important requirement for railway systems. Therefore, Annex III of the Directive in point 1.1.4. states that:

> *The design of fixed installations and rolling stock and the choice of the materials used must be aimed at limiting the generation, propagation and effects of fire and smoke in the event of a fire.*

On the one hand, such a statement is hardly objectionable; on the other, it is not precise enough to judge whether specific infrastructure or rolling stock fulfils the requirement posed. Still, this is perfectly fine since it is an essential requirement, which must be assessed by a notified body (formally accepted based on its competencies and procedures by a Member State and notified to the European Commission and other Member States) in line with the applicable rules.

Detailed rules applied by notified bodies (NBs) cannot be determined by NBs themselves as all NBs notified under the railway interoperability directive [1] are fully entitled to asses whether the essential requirements are met by different solutions manufactured, constructed, installed, delivered or utilised in all European Member States. Essential requirements are therefore linked with detailed requirements of a different status (not always mandatory) which can be found in four types of documents:

- Technical Specifications for Interoperability (TSIs), which are published as European Commission Regulations in the Official Journal (OJ) of the EU, available on the EU website (www.eur-lex.europa.eu); Links to individual regulations are available on the Agency website (www.era.europa.eu);
- European Union Agency for Railways' binding documents, available on the Agency website (www.era.europa.eu);
- European standards (ENs), parts of which are also indicated in the TSIs as mandatory, which are accepted as harmonised standards and listed in the OJ (series C), available on the EU website (www.eur-lex.europa.eu); and
- Binding documents jointly accepted by NBs, which are available on the NBRail website (www.nb-rail.eu).

It is therefore important to answer how NBs decide whether, for instance, a new type of rolling stock and its construction materials ensure appropriately low risk of generation, propagation and effects of fire and smoke in the event of a fire. One could point to the technical specification for interoperability relating to the "rolling stock — locomotives and passenger rolling stock" subsystem of the European Union rail system (LOC&PAS TSI [3]). While it does contain some requirements, the LOC&PAS TSI [3] is only part of the formal environment. Since risk assessment rules allow us to see the whole picture, including detailed requirements defined in the LOC&PAS TSI [3], such an approach was taken as a basis for this paper.

2.1.1. General Risk Assessment Principles

Figure 2.1.1 shows the general approach to risk applied through "safety engineering", a discipline of engineering aiming at ensuring that systems/devices/procedures provide an acceptable level of safety. This approach is further broken down into risk assessment and risk response.

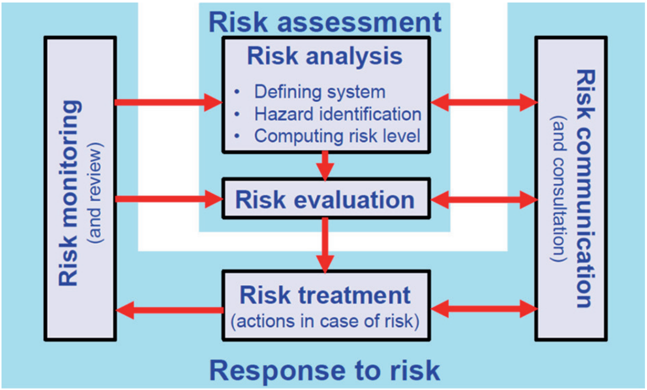

Figure 2.1.1. General risk assessment principles (source: a typical visualisation utilised in many risk-related publications)

Risk assessment comprises risk analysis and risk evaluation while risk response is subdivided into risk treatment, risk monitoring, and risk communication. The approach of choice is therefore directly based on risk. Risk as such, for railway-related purposes, is precisely defined in the CSM RA regulation [2] as:

the frequency of occurrence of accidents and incidents resulting in harm (caused by a hazard) and the degree of severity of that harm

Risk therefore significantly differs from hazard as the latter is non-quantifiable as a potential source of risk, whereas the former is associated with an expected frequency and expected harm. Examining the way how risk analysis, risk evaluation and safety are defined as follows in the CSM RA regulation:

'risk analysis' means systematic use of all available information to identify hazards and to estimate the risk;
'risk evaluation' means a procedure based on the risk analysis to determine whether an acceptable level of risk has been achieved;
'safety' means freedom from unacceptable risk of harm;

To determine whether fire safety is ensured, an assessment body must analyse all causes of fire and verify whether fire risk, expressed by the expected probability and expected harm, is below an unacceptable level. Achieving and documenting an answer in a way that would not be questioned by other NBs or users in accordance with the CSM RA regulation [2] is possible by applying codes of practice (CoP) or through comparison using a similar reference system (SRS) or explicit risk estimation (ERE). Acceptance principles may differ depending on individual risk, e.g. fire type, source, location, etc.

2.1.2. Codes of Practice and Similar Reference Systems as Fire Safety Risk Acceptance Criteria

Explicit risk estimation is usually a difficult risk assessment method, and as such, a reasonable risk assessment should be, insofar as possible, based first on codes of practice and then on comparisons to similar reference systems.

LOC&PAS TSI and EN Standards Requirements as Codes of Practice

The CSM RA regulation [2] requires documents that are deemed codes of practice to satisfy at least the following requirements:

(a) They must be widely recognised in the railway domain. If this is not the case, the codes of practice will have to be justified and be acceptable to the assessment body;
(b) They must be relevant for the control of the considered hazards in the system under assessment. Successful application of a code of practice for similar cases to manage changes and control effectively the identified hazards of a system in the sense of this Regulation is sufficient for it to be considered as relevant;
(c) Upon request, they must be available to assessment bodies for them to either assess or, where relevant, mutually recognise, […], the suitability of both the application of the risk management process and of its results.

In that respect, there is no doubt that the LOC&PAS TSI defining rolling stock-related requirements [3], the SRT TSI setting out requirements on safety in railway tunnels [4], the EN standards establishing fire requirements for rolling stock materials and components [5] and the EN standard specifying the acceptance procedure for running capability in case of fire on board of rolling stock [6] can and must be treated in their scope as codes of practice. A wide range of fire scenarios can therefore be assessed based on precise technical requirements. Still, some cases are not covered, e.g. fire on board rolling stock running on a long railway viaduct or bridge.

Possible Use of a Similar Reference Systems

The second-choice risk acceptance criterion is a comparison with a similar reference system. The CSM RA regulation [2] requires reference systems that satisfy at least the following requirements:

(a) it has already been proven in-use to have an acceptable safety level and would therefore still qualify for approval […] where […] is to be introduced;
(b) it has similar functions and interfaces as the system under assessment;
(c) it is used under similar operational conditions as the system under assessment;

(d) it is used under similar environmental conditions as the system under assessment.

While it is often possible to find another type of rolling stock that had been used, e.g., on a long railway viaduct or bridge, typically such rolling stock significantly differs in terms of construction, materials and components, making it unsuitable as a reference system due to factors like propulsion, digital components, cargo flammability, etc. As a result, an explicit risk estimation approach is necessary for certain fire scenarios.

2.1.3. Explicit Risk Estimation as a Fire Safety Risk Acceptance Criteria

Since RAMS standards [7, 8] fulfil the requirements for codes of practice, one could be led to believe that they belong to the risk acceptance approach described in section 3.1 above. That is not true, however, as RAMS standards concern only railway-specific explicit risk estimation methodology and do not directly define fire-related requirements.

There are five RAMS standards, all issued as ENs. Nonetheless, two of them — EN 50128 [..] dedicated to software development and EN 50159 [..] dedicated to the use of communication systems for safety-related exchange of data — are not relevant to fire safety. The use of both parts of the basic RAMS standard [7], which apply to the entire railway system, is frequently required based on the statements in the TSIs.

As an example, according to the LOC&PAS TSI [3], the safety requirements that are relevant to hot events relate particularly to the following scenarios:

4.2.5.3.5 Safety requirements

(1) 'failure in the passenger alarm system leading to the impossibility for a passenger to initiate the activation of brake in order to stop the train when train departs from a platform',
(2) 'failure in the passenger alarm system leading to no information given to the driver in case of activation of a passenger alarm',

In accordance with the provisions of the LOC&PAS TSI [3]:

… it shall be demonstrated that the risk is controlled to an acceptable level considering that the functional failure has typical credible potential to lead directly to 'single fatality and/or severe injury'.

The demonstration of conformity (conformity assessment procedure) is described in clause 6.2.3.5 of the LOC&PAS TSI. In contrast, the principles of developing risk analysis documents and gathering evidence of their acceptability as well as the rules for independent verification of such documents are detailed in the basic RAMS standard EN 50126, Part 1 and Part 2 [7].

RAMS Lifecycle

The documents in question must be created step by step during lifecycle phases, from concept to system acceptance. Their exact names, scopes and structures, as well as topics to be covered by individual documents at defined lifecycle phases, are defined in EN 50126-1 [7] and shown below in Figure 2.1.2 taken from that standard.

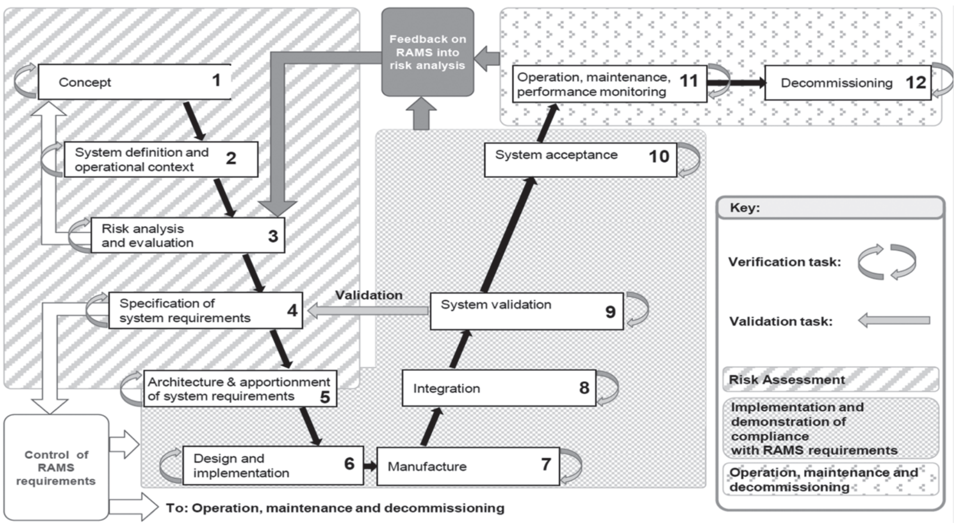

Figure 2.1.2. Safety-related lifecycle phases in the development of railway-related technical solutions (source: EN 50126-1 [7])

RAMS standards also define the subdivision of activities and relationships between experts involved in technical solution development. While one could indicate phase 3 — "risk analysis and evaluation" — as a key moment in which fire-related risks must be considered and described, these strongly depend on decisions taken as early as phases 1 and 2, when the solution and its operational context are defined. Many decisions taken in phases 4 to 9 must also be reflected in safety-related documents and influence the relevant solutions, e.g. the designs and/or materials chosen, requiring iterative upgrading of the risk analysis and evaluation.

Significant Change

RAMS standards are devoted to the development and acceptance of new systems. Although they include statements regarding the introduction of changes, the key binding requirements in that respect are expressed in EU regulation 2013/402 [2] (hereinafter referred to as "CSM RA" — common safety method on risk acceptance). It is vital to pay attention to the definitions of hazard, risk and safety, risk analysis, risk assessment, risk estimation, risk evaluation, risk acceptance and risk management as well as safety requirements and safety measures, as contained in the CSM RA. So important is the role of risk acceptance definitions that the CSM RA regulation's definitions were amended through regulation 2015/1136 [3] to ensure no ambiguity.

The CSM RA requires all change proposers to answer two key questions before they decide whether detailed analysis is required. The first is whether the change can influence safety, though it does not matter if safety is expected to increase or decrease. The second is whether the proposed change is significant or not. If it is, the risk acceptance procedure must be applied.

The decision on whether the change is significant is always based on expert judgement. Therefore, it is critical to include the experts' competencies in risk evaluation and assessment reports, which are verified by the appropriate assessment body. The expert group must determine significance based on six criteria: failure consequences, novelty, complexity, monitoring, reversibility and additionality. As an example, when using new potentially flammable materials in rolling stock construction, the failure consequences themselves already determine whether a change is significant, taking into account the credible worst-case scenario in the event of a fire. Such a change can, however, frequently be accepted under the relevant standard used as a code of practice — based on full conformity with EN 45545 [5]. Yet, some changes may be more complex. For instance, those related to new types, new methods, or new ambient or external circumstances must be treated as novelties. In many cases, it is important to consider complexity, e.g. for solutions which require specific staff competencies or tools. One example would be mechatronic solutions in running gear, which use rubber elements; these must be treated that way, particularly in relation to fire-related risks. Monitoring and reversibility criteria must be considered as at least partly related. Monitoring after the introduction of a change is insufficient if reversibility or additional safety measure(s) are not available. As an example, an emergency exit to be used in case of fire, requiring e.g. a conical hammer, must be analysed together with solutions ensuring the monitoring of hammer availability and safety measures to be applied in case of frequent thefts — like a steel cable securing the hammer to the vehicle wall near the emergency exit. Due to a tendency to view small changes as insignificant, each new change that is deemed insignificant on its own has to be examined in conjunction with all the earlier changes accepted as such. This is known as additionality. It should account for things like fire-related interactions between different types of materials used in the vehicle's design, as well as any on-board devices.

Any change which is deemed significant requires identifying risks, including fire risks, and applying one of the risk acceptance criteria. Codes of practice and reference systems should be used insofar as reasonably possible, but in some cases, explicit risk estimation is required. The CSM RA regulation [2] does not stipulate how to apply explicit risk estimation. This is, however, taken directly into account by RAMS standards [7, 8]. Explicit risk estimation can be quantitative or qualitative.

Quantitative Explicit Risk Estimation

It is theoretically possible to define future consequences of fire and the probability of its occurrence. Where these are credibly defined for different fire scenarios, they could be compared with the respective requirements to decide whether additional safety measures like additional, more efficient on-board fire detection and fire extinguishing systems are necessary.

The respective requirements could be the risk-related values set out in the national guidelines published by the National Safety Authorities established in each EU member state for railway safety supervision under the interoperability directive (the directive now in force was accepted by the EU Parliament in 2016 [1]), or in the European Union Agency for Railways' guidelines, or in RAMS standards [7, 8] which state that potentially catastrophic risks can be treated as acceptable when their probability is lower than 10^{-8} per hour per risk scenario, assuming that at the same time human errors in design, construction, operation and maintenance are appropriately minimised as described in RAMS standards for Safety Integrity Level 4 (SIL4).

In practice, using quantitative explicit risk estimation for fire-related risks is difficult, especially since different scenarios have to be considered. As such, the qualitative approach is applied much more frequently.

Qualitative Explicit Risk Estimation Based on RAMS Standards

Qualitative explicit risk estimation for railway-related risks can be based on different qualitative approaches, which fulfil the formal requirements of the CSM RA regulation [2]. It is formally allowed to apply different methods. The CSM RA does not indicate the exact methods; however, RAMS standards [7, 8] do. In view of EN 50126-2 Annex F [7], the following techniques/methods can be treated as recommended:

- FMECA with ETA/FTA support — Failure Mode, Effects and Criticality Analysis (FMECA) as defined in IEC 60812:2006, with support of the Event Tree Analysis (ETA) as defined in IEC 62502:2010 and Fault Tree Analysis (FTA) as defined in IEC 61025:2010; or
- Markov diagrams as defined in IEC 61165:2006; or
- Risk graphs as defined in IEC 61508-5:2010 Annex E.

Moreover, EN 50126-1 Annex C [7] defines a risk matrix calibrated for the acceptance of the railway-related risks (see Figure 2.1.5), which is based on frequency levels (see Figure 2.1.3) and severity categories (see Figure 2.1.4), defined based on railway transport characteristics and experience accumulated over dozens of years of railway operations.

Frequency level	**Description**	**Example of a frequency range based on a single item operating 24 h / day**	**Example of equivalent occurrence in a 30 year lifetime of a single item operating 5000 h / year**
		Expected to happen	
Frequent	Likely to occur frequently. The event will be frequently experienced.	more than once within a period of approximately 6 weeks	more than about 150 times
Probable	Will occur several times. The event can be expected to occur often.	approximately once per 6 weeks to once per year	about 15 to 150 times
Occasional	Likely to occur several times. The event can be expected to occur several times.	approximately once per 1 year to once per 10 years	about 2 to 15 times
Rare	Likely to occur sometime in the system life-cycle. The event can reasonably be expected to occur.	approximately once per 10 years to once per 1 000 years	perhaps once at most
Improbable	Unlikely to occur but possible. It can be assumed that the event may exceptionally occur.	approximately once per 1 000 years to once per 100 000 years	not expected to happen within the lifetime
Highly improbable	Extremely unlikely to occur. It can be assumed that the event will not occur.	once in a period of approximately 100 000 years or more	extremely unlikely to happen within the lifetime

Figure 2.1.3. Frequency levels for the railway-specific risk acceptance matrix (source: EN 50126-1 Annex C [7])

Severity category	**Consequences to persons or environment**	**Consequences on service/property**
Catastrophic	• Affecting a large number of people and resulting in multiple fatalities, and/or • extreme damage to the environment	Any of the below consequences in presence of consequences to persons or environment
Critical	• Affecting a very small number of people and resulting in at least one fatality, and/or • large damage to the environment	Loss of a major system
Marginal	• No possibility of fatality, severe or minor injuries only, and/or • minor damage to the environment	Severe system(s) damage
Insignificant	• Possible minor injury	Minor system damage

Figure 2.1.4. Severity categories for the railway-specific risk acceptance matrix (source: EN 50126-1 Annex C [7])

Frequency of occurrence of an accident (caused by a hazard)	Risk Acceptance Categories			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Rare	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Undesirable
Highly improbable	Negligible	Negligible	Negligible	Tolerable
	Insignificant	**Marginal**	**Critical**	**Catastrophic**
	Severity of an accident (caused by a hazard)			

Risk Acceptance Category	Actions to be applied
Intolerable	The risk shall be eliminated
Undesirable	The risk shall only be accepted if its reduction is impracticable and with the agreement of the railway duty holders or the responsible Safety Regulatory Authority.
Tolerable	The risk can be tolerated and accepted with adequate control (e.g. maintenance procedures or rules) and with the agreement of the responsible railway duty holders.
Negligible	The risk is acceptable without the agreement of the railway duty holders.

Figure 2.1.5. Railway-specific risk acceptance matrix (source: EN 50126-1 [7] Annex C)

It is vital to analyse all fire scenarios which were not accepted due to codes of practice or similar reference systems. It must also be stressed that applying the matrix-based approach requires the involvement of fire experts able to credibly assess the frequency levels and severity categories. Moreover, unlike in Failure Mode, Effects and Criticality Analysis (FMECA), the railway-specific risk acceptance matrix includes not three but four risk acceptance categories. The additional one is subject to acceptance by the National Safety Authorities established in individual EU Member States under the Railway Safety Directive (Directive 2016/798).

The explicit risk estimation based on the risk acceptance matrix can be applied to all different fire scenarios; however, in some cases, i.e. in relation to rolling stock intended for use in railway tunnels, a precisely defined explicit risk estimation is required.

Explicit Risk Estimation Based on Running Capability With Fire on Board

Explicit risk estimation for rolling stock intended for use in railway tunnels must be based on the standard dedicated to the assessment and acceptance of running capability with fire on board, i.e. EN 50553:2012 [6]. This is required because the standard in question is indicated as mandatory by the TSI dedicated to safety in railway tunnels — the SRT TSI [4].

Running capability assessment is based on five decision boxes. The relationship between them is shown in Figure 2.1.6.

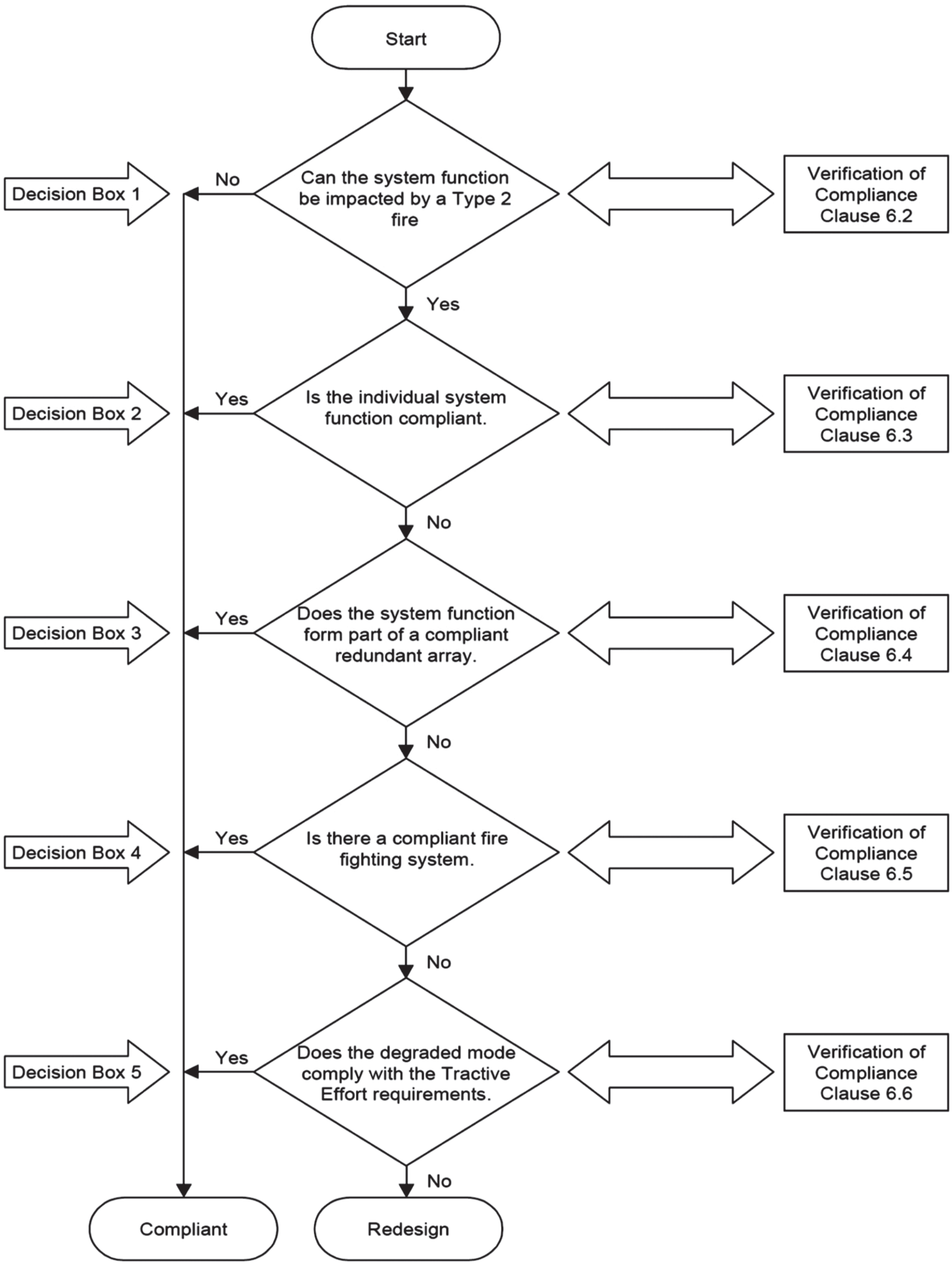

Figure 2.1.6. Running capability decision boxes (source: EN 50553 [6])

Decision Box 1 (clause 6.2 of the EN 50553 [6]) is based on the assessment of whether a Type 2 fire is possible. The standard defines three types of fire which are related to rolling stock materials, fire ignition models and power. Type 2, which is the one requiring running capability, is defined in terms of power as 75 kW for 2 minutes followed by 150 kW for 8 minutes. If such a fire can be excluded considering passenger areas, including any vandalised seats, passenger luggage and power equipment, including fuel tanks and engines, the subsequent decision boxes are not required.

Decision Box 2 (clause 6.3 of the EN 50553 [6]) is based on ensuring the driver's resilience against a Type 2 fire, taking into account cables, technical cabinets, pneumatic and hydraulic equipment, combustive fluids as well as signalling, communication and control equipment. It must be proven that a Type 2 fire would not cause smoke/toxic fume concentrations in the cab that would impair the driver's ability to operate, that openable windows are available in the cab, that ventilation/air conditioning would allow the driver to continue driving or that the cab is equipped with smoke hood(s) offering at least equivalent protection.

Decision Box 3 (clause 6.4 of the EN 50553 [6]) concerns redundant arrays, construed as the multiplication of all key functions/equipment to ensure that, when necessary, rolling stock will be able to reach the end of the tunnel or a safe area, as defined in the technical specification for interoperability relating to "safety in railway tunnels".

Decision Box 4 (clause 6.5 of the EN 50553) is related to the availability of the appropriate on-board firefighting system, whereas Decision Box 5 (clause 6.6 of the EN 50553) requires examining and positively verifying the fire-related risks in degraded modes of operation.

Therefore, since some detailed requirements are indicated and some assessments depend on expert knowledge and judgements, this approach can be treated as partly quantitative and partly qualitative.

2.1.4. Hazard Log and Duties of the Railway Duty Holders

Fire risk cannot be fully addressed by the industry, as it depends on the activities of railway undertakings and infrastructure managers. The CSM RA regulation [2, 3] directly indicates technical, operational and organisational changes as those possibly affecting safety but does not provide a basis for the subdivision of responsibility between industry and railway companies.

Such a subdivision is however defined in RAMS standards and shown in Figure 2.1.7.

RAMS standards define "railway duty holders" as:

- companies responsible for rolling stock operation, i.e. "railway undertakings", as per the railway interoperability directive and the TSIs, which are formally recognised by the regulations under this directive,

- companies responsible for railway traffic planning and implementation, i.e. “infrastructure managers”, as per the directive and the TSIs, and
- companies providing rolling stock and infrastructure maintenance.

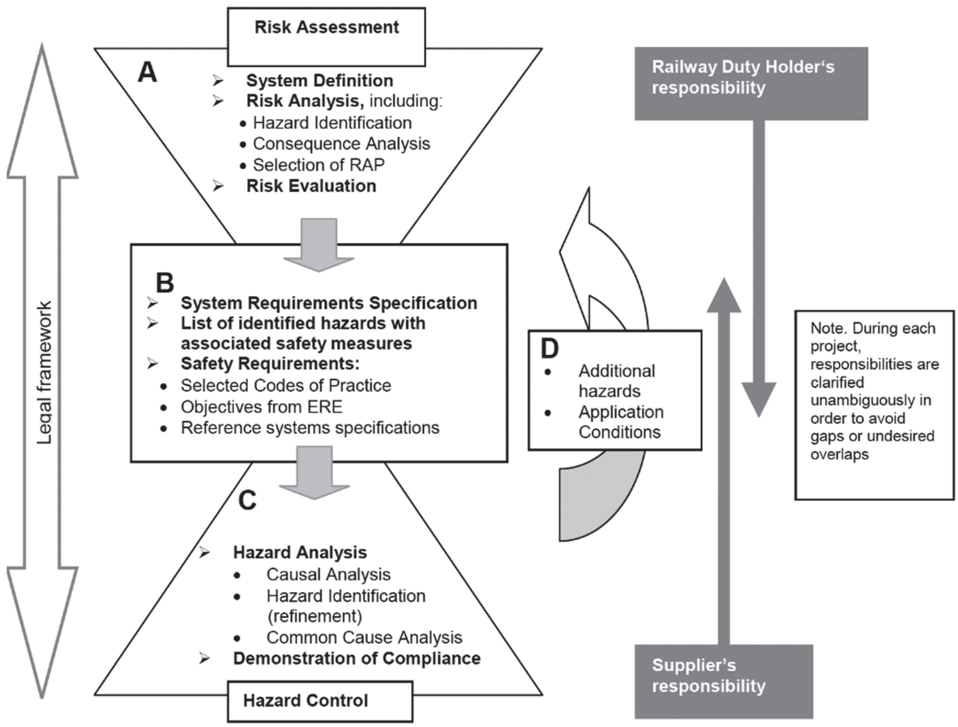

Figure 2.1.7. Subdivision of responsibility between industry and railway companies (source: EN 50126-1 [5])

The railway duty holders act under the railway safety directive, apply the CSM RA regulation and are obliged to use risk analysis to verify the acceptance of different kinds of risks, including those related to fire safety, as shown in the upper part of the “hourglass” in Figure 2.1.7. Risk assessments by duty holders do not consider technical and technological characteristics of the relevant solutions; these are provided by industry and, therefore, industrial partners are also required to undertake hazard analysis, as shown in the lower part of the “hourglass” in Figure 2.1.7. Duty holders use analyses to set out their requirements, e.g. by indicating the codes of practice with which the proposed solutions must comply, as well as to verify that their hazard logs list the complete range of hazards and the appropriate safety measures (staff, tools, procedures, etc.) for those hazards to ensure no unacceptable risk in operation. On the other hand, industrial partners use their analyses to show that the identified risks are deemed negligible or must be associated with Safety Related Application Conditions (SRAC), which have to be reflected in duty holder hazard logs for all hazards associated with tolerable and undesirable risks, as accepted by duty holders themselves or by the National Safety Authorities on their request.

Both duty holders and industrial partners must consider scenario-based fire safety risks, taking into account the locations, ignition sources, flammability of materials, presence of staff and passengers, availability of fire and smoke detectors and fire extinguishing systems, etc., and provide evidence that there is no unacceptable risk in all reasonably imaginable scenarios.

2.1.5. Conclusions

The following conclusions were drawn based on the above considerations:

- The risk management processes must be applied by both the railway industry and railway duty holders, construed as railway undertakings and railway infrastructure managers and companies responsible for maintenance. Both types of stakeholders are entitled to apply qualitative and quantitative approaches to hazards. All three risk acceptance principles, namely codes of practice, reference systems and explicit risk estimation, require stakeholders to document fire safety decisions, include them in hazard logs and apply safety measures associated with them;
- The documents which can or even must be treated as codes of practice in relation to fire safety are already available and cover many fire safety-related risks; however explicit risk estimation is necessary in some cases;
- Since the acceptance of the fourth railway package (see Regulation (UE) 776/2019 [1]), the recently amended RAMS standards, especially EN 50126-1 [7] and EN 50126-2 [7], are presently directly linked with Technical Specifications for Interoperability and must be applied to all structural subsystems, including in relation to fire safety. Therefore, using the railway-specific risk acceptance matrix under EN 50126-1 [7] Annex C is recommended in such cases;
- Applying an approach based on the CSM RA regulation and RAMS standards for fire safety and hazardous hot events is vital wherever codes of practice based on EN 45545 [..] and EN 50553 [..] are insufficient. Therefore, all stakeholders, especially rolling stock producers, stations and tunnels designers and constructors, rolling stock users and infrastructure managers, as well as certification bodies involved in railway-related acceptance processes, should be intricately familiar with the CSM RA regulation and RAMS standards.

Bibliography

Legal and Normative Acts, Guidelines

[1] Directive 2016/797 of 16 May 2016 on the interoperability of the rail system in the European Union.

[2] Commission Regulation No 402/2013 of 30 April 2013 on the common safety method for risk evaluation and assessment.

[3] Commission Regulation (EU) No 1302/2014 of 18 November 2014 concerning a technical specification for interoperability relating to the 'rolling stock — locomotives and passenger rolling stock' subsystem of the rail system in the European Union.

[4] Commission Regulation (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to 'safety in railway tunnels' of the rail system of the European Union.

[5] EN 45545 — Railway Applications — Fire Protection on Railway Vehicles:
- Part 1: General;
- Part 2: Requirements for Fire Behaviour of Materials And Components;
- Part 3: Fire Resistance Requirements for Fire Barriers;
- Part 4: Fire Safety Requirements for Railway Rolling Stock Design;
- Part 5: Fire Safety Requirements for Electrical Equipment Including That of Trolley Buses, Track Guided Buses and Magnetic Levitation Vehicles;
- Part 6: Fire Control and Management Systems;
- Part 7: Fire Safety Requirements for Flammable Liquid and Flammable Gas Installations.

[6] EN 50553:2012/A2: 2020 — Railway Applications — Requirements for Running Capability in Case of Fire on Board of Rolling Stock.

[7] EN 50126-1:2017 Railway Applications — The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS):
- Part 1: Generic RAMS Process;
- Part 2: Systems Approach to Safety.

[8] EN 50129:2018 Railway Applications — Communication, Signalling and Processing Systems — Safety Related Electronic Systems for Signalling.

2.2. Assessment and Certification of Rolling Stock Subsystems in Accordance With EN 45545-2

2.2.1. EN 45545

The standard EN 45545 — Fire Protection on Railway Vehicles — comprises 7 Parts [4–11], as presented in subchapter 1.1 and below in Figure 2.2.1.

The Safety Objective of the EN 45545 is to protect passengers and staff from the effects of on-board fire.

This is effected through several measures[1]:

- minimising the probability of a fire event;
- limiting fire propagation in terms of speed and size;
- detecting incipient fires;
- minimising the release of heat, smoke and toxic gases;
- fire suppression.

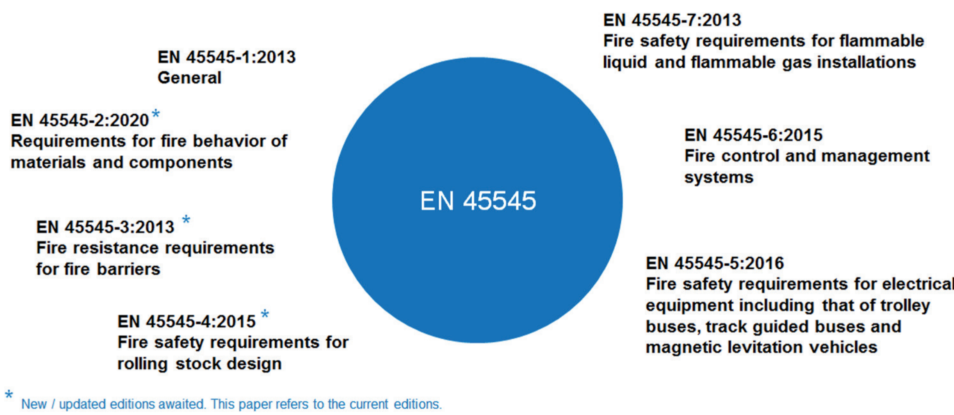

Figure 2.2.1. EN 45545 (source: author's own work)

The Fire Protection Objectives are taken into consideration in the context of the vehicle's operation and design category[2].

2.2.2. Assessment and Certification in Accordance With EN 45545

Legislative and Normative Framework

Rolling stock fire protection (and general railway sector safety) in the EU is governed by a complex framework, which is usually illustrated using a pyramid structure (Figure 2.2.2).

At the lowest level are the standards, guidelines, technical rules, technical procedures and provisions of the private sector, which are adopted for a product based on a private agreement between the parties. EN standards would typically fall into this category. The present paper refers to this area as the "private sector".

1 Ibidem.

2 Ibidem, p. 13.

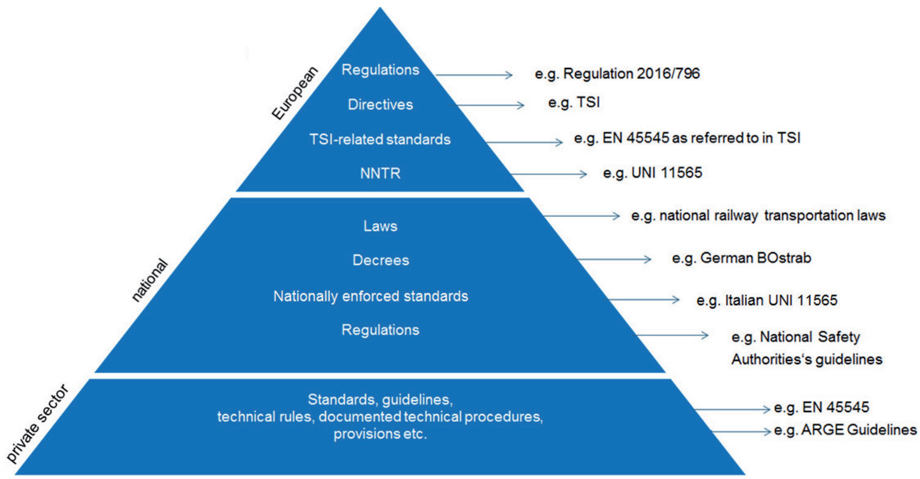

Figure 2.2.2. Legislative and normative framework (source: author's own work)

The middle level includes laws, decrees, standards and regulations defined by a single Member State of the EU. They are mandatory at the national level and are enforced by central or regional/local authorities. An example from this category is the German legislative decree *Strassenbahn Bau- und Betriebsordnung* (BOStrab), covering the construction and operation of tramways and metros.

The summit of the "pyramid" is made up of the laws and regulations defined at the EU level. These are obligatorily applied across all Member States and take precedence over national laws. Laws and regulations defined at the EU level may include EU regulations, EU directives and Notified National Technical Rules (NNTR). Some (EN) standards fall into this category as well, insofar as they are enforced directly by EU regulations or EU directives. EN 45545-2 and UNI 11565 (specifically for Italy) are typical examples, as they are expressly referred to in Commission Regulation No 1302/2014 (LOC&PAS TSI). Notably, the LOC&PAS TSI refers to the old 2013 edition of EN 45545-2, not the latest 2020 version[3]The two upper levels of the pyramid are identified as the "regulated sector".

As such, the two main areas for assessment/certification to EN 45545 can be defined as follows:

1. Assessment in the private sector.
2. Assessment in the regulated sector (national or EU in the context of this paper).

Assessments in the private sector and the EU-regulated sector are presented in the next sections.

[3] See Commission Regulation (EU) No 1302/2014 of 18 November 2014 concerning a technical specification for interoperability relating to the 'rolling stock — locomotives and passenger rolling stock' subsystem of the rail system in the European Union, Appendix H, section H.2, p. 241.

Assessment and Certification in the Private Sector

An assessment and certification in the private sector is not legally required. It is contracted by manufacturers to demonstrate their products' conformity to a standard. An assessment and certification in the private sector could, for example, be focused on general market access or fulfilment of specific customer requirements. It can be used in the main railway market, but also in such sectors as tramways, metros and APMs.

The result of assessment and certification in the private sector is usually an assessment report and, in the case of a positive outcome, also a certificate.

EN ISO/IEC 17020[4] and EN ISO/IEC 17065[5] define the framework in which an independent assessment and certification process in the private sector takes place.

Independent assessment and certification of a product is a *third-party conformity assessment*[6], and as such, it is an activity in which an independent party (third party) evaluates whether the relevant requirements, e.g. under EN 45545-2, are fulfilled by the *object of conformity assessment*. Objects of conformity assessment may vary in nature; they may be processes, design types or physical specimens. However, in the context of this paper, such objects are rolling stock materials, components, equipment or subsystems, or entire vehicles, and are generically referred to as "products".

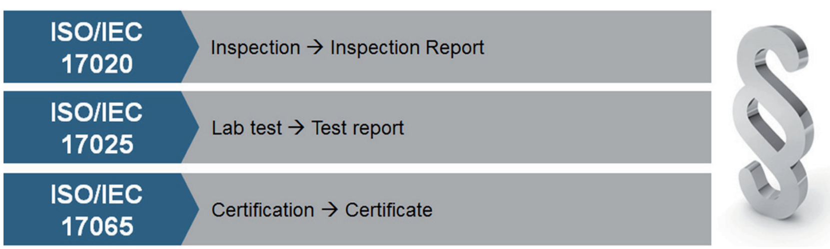

Figure 2.2.3. A framework for third-party independent assessment and certification (source: author's own work)

All material fire behaviour tests, if required by EN 45545-2, must be carried out by laboratories accredited for these tests according to EN ISO/IEC 17025[7].

4 EN ISO/IEC 17020:2012.

5 Ibidem.

6 All terms in Italics reflect the terminology used in EN ISO/IEC 17020:2012, EN ISO/IEC 17025:2017 and EN ISO/IEC 17065:2012.

7 EN 45545-1: 2013, section 8.2, p. 17.

Product inspections can be performed by an inspection body accredited to EN ISO/IEC 17020:2012 for the relevant scope. The inspection body must examine the product and determine its conformity with the requirements of such standards as EN 45545-2. This examination may also include any material fire behaviour test reports issued by laboratories accredited for these tests according to EN ISO/IEC 17025.

The conformity assessment is therefore based on test reports (laboratory test reports), inspection or a combination of the two.

A successful conformity assessment enables the certification of conformity to, e.g., EN 45545-2.

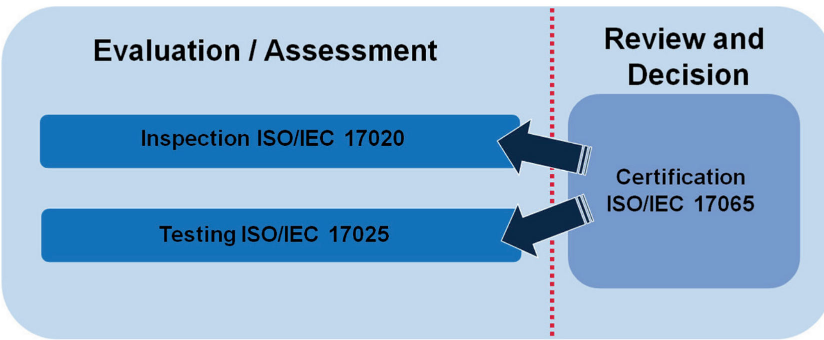

Figure 2.2.4. Assessment and certification process in the private sector (source: author's own work)

A certification is a third-party *attestation* related to the object of conformity assessment, which is issued by a certification body accredited to EN ISO/IEC 17065 for the relevant scope. It attests to conformity based on the certification body's *decision* that the fulfilment of the requirements, e.g. under EN 45545-2, has been demonstrated.

Notably, all parts of EN 45545 apply to the conformity assessment and certification of the product to EN 45545. Nonetheless, only the parts which are relevant to the specific product may be adopted, e.g. EN 45545-2.

This means that, for example, only material requirements set out in EN 45545-2 will apply to a specific type of material used on board a vehicle; however, all 7 parts of EN 45545 will apply to the entire vehicle.

Assessment and Certification in the EU-Regulated Sector

The assessment and certification in the EU-regulated sector (EC verification) aims to provide the applicant with an EC certification, allowing the relevant product to enter the European railway market. It is required by law for each product that is intended to be used in the interoperable rail network of the European Union.

EC verification must be performed by a notified body (NoBo). A notified body is an organisation that fulfils the relevant requirements and has been designated by a Member State to the European Commission to carry out conformity assessment according to a directive[8].

The relevant TSI for rolling stock is the already mentioned Commission Regulation No 1302/2014 ("LOC&PAS TSI"), which refers to specific rolling stock fire protection issues.

Section 4.2.10 of the LOC&PAS TSI defines requirements regarding fire protection. A direct reference to EN 45545-2:2013+A1:2015 is made in Appendix J-1, index 58–59. To be precise, sections 4.2.10.2.1 and 4.2.10.2.2 indicate EN 45545-2:2013 as applicable to general material requirements and flammable liquids. EC verification must therefore be conducted in accordance with EN 45545-2:2013+A1:2015[9].

The procedure for EC verification, as set out in EU Directive 2016/797[10], must be followed.

The detailed modules for the EC verification of subsystems are defined in Commission Decision 2010/713/EU[11]. The following applies to rolling stock subsystems to which fire protection belongs[12]:

- Module SB — EC-type examination.
- Module SD — EC verification based on quality management system of the production process.
- Module SF — EC verification based on product verification.
- Module SH1 — EC verification based on full quality management system plus design examination (Figure 2.2.5).

The assessment must then be performed according to a combination of modules defined by Commission Regulation No 1302/2014 ("LOC&PAS TSI")[13].

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8 See https://ec.europa.eu/growth/tools-databases/nando/index.cfm.

9 See section 0.

10 Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union, Annex IV.

11 2010/713/EU: Commission Decision of 9 November 2010 on modules for the procedures for assessment of conformity, suitability for use and EC verification to be used in the technical specifications for interoperability adopted under Directive 2008/57/EC of the European Parliament and of the Council, Annex I

12 See Consolidated Text, 11 March 2020, Commission Regulation (EU) No 1302/2014 of 18 November 2014 concerning a technical specification for interoperability relating to the 'rolling stock — locomotives and passenger rolling stock' subsystem of the rail system in the European Union, section 6.2.2 (1), p. 155.

13 Ibidem.

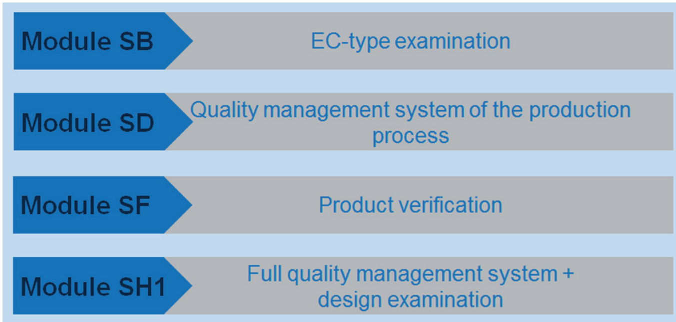

Figure 2.2.5. Modules for EC verification of subsystems (source: author's own work)

Upon completion of the assessment, the notified body must draw up an evaluation report listing the performed activities and their outcomes[14].

Since fire protection is an intermediate stage of the rolling stock subsystem, a notified body cannot issue an EC-type examination certificate for fire protection alone. As such, in this case, the final result of the conformity assessment would be an Intermediate Statement Verification certificate (EC ISV certificate under Article 18(4) of Directive 2008/57/EC[15]), in accordance with the selected module(s).

2.2.3. Examples

Fire Protection Assessment and Certification of On-Board Electronic Equipment (Private Sector)

This example considers a "small" on-board electronic/electromechanical device like an E/E/PE control unit or a router.

In this case, the manufacturer may demonstrate conformity under clause 4.2. h) of EN 45545-2:2020[16] (Figure 2.2.6).

The clause in question states that mechanical or electrical components enclosed in technical cabinets do not need to be analysed for conformity in some specific cases[17].

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[14] See 2010/713/EU: Commission Decision of 9 November 2010 on modules for the procedures for assessment of conformity, suitability for use and EC verification to be used in the technical specifications for interoperability adopted under Directive 2008/57/EC of the European Parliament and of the Council, Annex I, p. 30.

[15] Ibidem, p. 31.

[16] Conformity may be demonstrated in other ways under the relevant clauses of EN 45545-2:2020. The approach used is illustrative only and is not possible under EN 45545-2:2013+A1:2015.

[17] Refer to EN 45545-2:2020, section 4.2 h), p. 12.

One of these cases could apply to the E/E/PE control unit or router — the object of the conformity assessment — e.g. if the housing contains only mechanical or low-power electrical equipment, the cabinet walls are closed and made out of aluminium, steel or glass, the internal volume is ≤ 0.1 m³ and openings are covered by connectors or switches and are negligible.

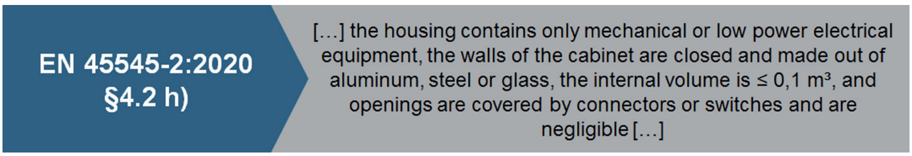

Figure 2.2.6. Applicable requirements based on the chosen example [5]

Should the manufacturer opt to make use of this clause, the next step would be to produce evidence of this conformity and provide it to the inspection organisation for assessment/certification. Typical examples of such evidence include drawings, material lists and descriptions of the type of housing and connectors.

The inspection organisation would then evaluate the validity of this evidence and produce an inspection report in accordance with its accreditation, as per EN ISO/IEC 17020:2012.

The inspection report would then be the basis for a certification (process) performed by the certification organisation under EN ISO/IEC 17065:2012. This organisation would analyse the evidence of conformity provided (inspection report with a positive conclusion) and decide on certification.

The final result would be the certificate of conformity to EN 45545-2:2020 issued by the certification organisation — in the case of a positive certification decision (Figure 2.2.7).

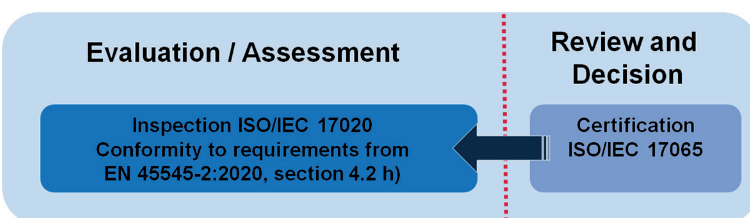

Figure 2.2.7. Assessment and certification process for the chosen example (source: author's own work)

EC Verification of a Door System in Regard to Fire Protection (EU-Regulated Sector)

This second example represents the case of a door system which may be assessed in terms of conformity to LOC&PAS TSI, as regards the fire protection requirements.

Applicable fire protection requirements are given in section 4.2.10. Generally, the detailed material requirements under section 4.2.10.2.1, with reference to Appendix J-1, index 58, will apply to door system materials (Figure 2.2.8).

LOC & PAS TSI technical requirements – fire protection

4.2.10.2. 1 Material requirements

•1) fire behaviour properties, such as flammability, smoke opacity and toxicity

•2) compliance with requirements of the specification referenced in Appendix J-1, index 58 (EN 45545-2)

•3) time limit 5 years of certificates to prove compliance of a material with the standard

Figure 2.2.8. Fire protection material requirements from the LOC&PAS TSI [1]

Appendix J-1, index 58, defines EN 45545-2:2013+A1:2015 as the applicable standard. The manufacturer (or applicant) must demonstrate conformity to EN 45545-2:2013+A1:2015 and provide the notified body with the relevant technical documentation, e.g.:

- general door system drawings,
- drawings of the main subsystems (single doors, door drives, door steps…),
- parts lists,
- combustible materials list[18],
- material fire behaviour test reports[19],
- if available, EN 45545-2:2013+A1:2015 conformity assessment reports and certificates for subsystems[20].

Detailed tasks of the notified body vary depending on the module selected (see section 2.3). In this paper, module SB — EC-type verification was chosen as an example. In this case, the assessment tasks of the notified body are as follows:

- examining the technical documentation provided to assess the design's conformity to EN 45545-2:2013+A1:2015,
- inspecting a sample production type to verify that the specimen has been manufactured in conformity to EN 45545-2:2013+A1:2015 and the technical documentation.

18 FCIL — Fire Certificate Inventory List, UNIFE Doc.TGF.03 is a format widely adopted for this purpose.

19 From test laboratories accredited in accordance with EN ISO/IEC 17025:2017, for the relevant scope.

20 These could be the result of a private sector assessment/certification as presented in section 2.2 of this paper.

The notified body would then draw up an evaluation report (EC verification report) listing the performed activities and their results.

In the case of a positive evaluation, having verified that the type complies with EN 45545-2:2013+A1:2015, the notified body would issue an EC ISV Module B certificate of conformity to EN 45545-2:2013+A1:2015 (Figure 2.2.9).

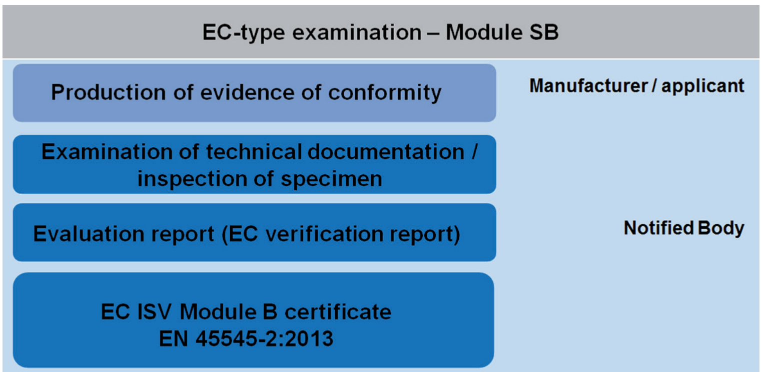

Figure 2.2.9. EC verification process for the chosen example (source: author's own work)

2.2.4. Conclusions

Assessment and certification of rolling stock components, subsystems and entire vehicles to EN 45545 Parts 1–7 may be performed for both private and EU-regulated sectors.

The two cases must be framed in different contexts:

A private sector assessment and certification is not legally required and is usually contracted by a manufacturer of a certain product to demonstrate the product's conformity to EN 45545. As such, its aim could be, for example, general market access or meeting specific customer requirements. It can be used in the main railway market, but also in such sectors as tramways, metros and APMs.

The EU-regulated sector assessment and certification (EC verification) aims to provide the applicant with an EC certification, allowing the relevant product to enter the European railway market. It is required by law for each product that is intended to be used in the interoperable rail network of the European Union.

A private sector assessment and certification is performed by an independent party (third party). Its final results are an assessment/evaluation report and an inspection certificate.

The EU-regulated sector assessment and certification (EC verification) is performed by a notified body; the final result in terms of fire protection compliance may be an Intermediate Statement Verification certificate.

Bibliography

Legal and Normative Acts, Guidelines

[1] Consolidated Text, 11 March 2020, Commission Regulation (EU) No 1302/2014 of 18 November 2014 concerning a technical specification for interoperability relating to the ‘rolling stock — locomotives and passenger rolling stock’ subsystem of the rail system in the European Union.

[2] Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union.

[3] 2010/713/EU: Commission Decision of 9 November 2010 on modules for the procedures for assessment of conformity, suitability for use and EC verification to be used in the technical specifications for interoperability adopted under Directive 2008/57/EC of the European Parliament and of the Council.

[4] EN 45545-1:2013 — Railway Applications. Fire Protection on Railway Vehicles. General.

[5] EN 45545-2:2020 — Railway Applications. Fire Protection on Railway Vehicles. Requirements for Fire Behaviour of Materials and Components.

[6] EN 45545-2:2013+A1:2015 — Railway Applications. Fire Protection on Railway Vehicles. Requirements for Fire Behaviour of Materials and Components.

[7] EN 45545-3:2013 — Railway Applications. Fire Protection on Railway Vehicles. Fire Resistance Requirements for Fire Barriers.

[8] EN 45545-4:2015 — Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Rolling Stock Design.

[9] EN 45545-5:2016 — Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Electrical Equipment Including That of Trolley Buses, Track Guided Buses and Magnetic Levitation Vehicles.

[10] EN 45545-6:2015 — Railway Applications. Fire Protection on Railway Vehicles. Fire Control and Management Systems.

[11] EN 45545-7:2013 — Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Flammable Liquid and Flammable Gas Installations.

[12] EN ISO/IEC 17020 — Conformity assessment — Requirements for Performance of Various Types of Bodies Performing Inspection.

[13] EN ISO/IEC 17025 — General Requirements for the Competence of Testing and Calibration Laboratories.

[14] EN ISO/IEC 17065 — Conformity Assessment — Requirements for Bodies Certifying Products, Processes and Services.

3 Engines, Electrical and Electronic Equipment of Rail Vehicles — Assessment and Protection

The purpose of active fire protection measures installed in rail vehicles is as follows:

- detection of fire in its initial stage,
- event alerting,
- extinguishing the fire in its initial stage of development,
- enabling efficient evacuation,
- minimising the danger area.

The above measures include fire detection devices, alarm systems, shutdown equipment, information and communication systems, emergency lighting systems, emergency braking systems and extinguishing systems (water sprinklers and mist, steam, foam, gas, aerosol, powder and inerting systems). They are subject to systematic development and improvement.

This section describes the Italian experience developed over the past ten years with innovative fire protection systems designed to handle increased risk levels posed by Thermal Engines and High-Power Equipment on several platforms.

Several solutions have been used for the protection of critical areas, including using redundant and multimodal detection strategies in engine rooms, adopting various firefighting technologies, certifying fire solutions for Safety Integrity Levels up to SIL2, close integration with onboard communication and monitoring systems, condition-based maintenance strategies and purposeful fire reaction procedures at the vehicle level, which are all beneficial to the effectiveness of protection.

Below are some examples of protection strategies and solutions adopted to protect technical areas housing combustion engines or power equipment on board rolling stock. An outline of the strategy adopted by the authors to ensure compliance with the requirements of the latest standards is presented as well.

The next section presents a holistic approach to the assessment of electrical and electronic devices installed in rail vehicles in terms of fire protection in accordance with the requirements of the EN 45545 series of standards [1–7]. This procedure includes stages such as design, production and application in various electrical and electronic configurations (elements/subsystems).

Bibliography

Legal and Normative Acts, Guidelines

[1] EN 45545-1 Railway Applications. Fire Protection on Railway Vehicles. General,

[2] EN 45545-2 Railway Applications. Fire Protection on Railway Vehicles. Requirements for Fire Behaviour of Materials and Components.

[3] EN 45545-3 Railway Applications. Fire Protection on Railway Vehicles. Fire Protection on Railway Vehicles — Fire Resistance Requirements for the Barriers.

[4] EN 45545-4 Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Railway Rolling Stock Design.

[5] EN 45545-5 Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements for Electrical Equipment Including That of Trolley Buses, Track Guided Buses and Magnetic Levitation Vehicles.

[6] EN 45545-6 Railway Applications. Fire Protection on Railway Vehicles. Fire Control and Management Systems.

[7] EN 45545-7 Railway Applications. Fire Protection on Railway Vehicles. Fire Safety Requirements For Flammable Liquid and Flammable Gas Installations.

3.1. Most Recent Experiences in the Protection of Rolling Stock Diesel Engines with an Innovative Approach

The last ten years have seen an unprecedented change in the overall scenario of rolling stock fire protection in Europe. The Italian Entity for Standardisation published the UNI CEI 11170 for the first time in November 2005, after the standard had been discussed and circulated for some time in draft form. The new standard was intended to better define the classification of fire risk levels and prevention measures to be adopted in railway vehicles and was divided into three parts: part one, containing "General principles"; part two, describing the mandated design criteria for fire containment measures, signalling and alert systems and evacuation measures; and part three (perhaps the most insightful), setting out the tests required for non-metallic materials, with the relevant limits of acceptability.

By that time, other European countries were almost ready for regulatory amendments as well. Indeed, 1989 saw the establishment of an international working group to develop a new European standard, and in the late 1990s, the European Commission approved funding for vital research & development work, including such European projects as FIRESTARR and TRANSFEU. These projects were established to support the work of CEN/TC256/WG1 and CENELEC/TC9X/WG3 for drafting part 2 of a new 7-part European Fire Standard and eventually contributed to the shaping of EN 45545 (Railway Applications — Fire Safety on Railway Vehicles), which was published by CEN and CENELEC in March 2013.

The release of EN 45545 marked a crucial step ahead in the progress of fire codes for rolling stock in Europe, especially since the new standard was designed to be a "Harmonised norm" under EC regulation No 1025/2012, as per UE directive 2008/57/CE, making it binding for all countries within the European Railway system.

Because of the approval of this new main standard, all European countries had to withdraw their national standards and rules after a transition period of 36 months, and this also included the former Italian Standard UNI 11170, which was abandoned in late March 2016.

The definition and adoption of EN 45545 in Europe constituted a major and extensive change in industry standards. This was because different European countries had discrete systems and production processes, including the machinery and technology used in the manufacturing of rolling stock materials and components, and each European country had developed various methods for testing and assessing the level of fire risk. At the same time, several faults causing fires on trains were experienced due to a variety of reasons, e.g. failures in the braking system, electrical problems and arson, thus creating strong pressure for the development of a common standard.

The evolution of the rolling stock fire protection scenario was completed in the same period along with the issue of Regulation EU No 1302/2014, which was adopted in November 2014 and established a technical specification for interoperability (TSI) relating to the "rolling stock — locomotives and passenger rolling stock" subsystem of the European Union rail system. The new TSI uses EN45545 as its main pillar in the field of fire safety and also refers to another vital 2013 standard, i.e. EN50553 "Railway Applications — Requirements for Running Capability in Case of Fire on Board of Rolling Stock". The latter specifies requirements for running capability under fire conditions which apply to passenger-carrying rolling stock, effectively completing the new European framework for train fire safety.

The development of rolling stock fire standards in Europe is likely far from over, as the needs for further evolution arise from time to time within the user community. Following the entry into force of the technical pillar of the Fourth Railway Package (Regulation 2016/796), the European Union Agency for Railways replaced and succeeded the European Railway Agency, and its latest work on the statistics of railway safety in Europe [3] shows a steady decrease in significant accidents and resulting casualties between 2010 and 2018. Still, this decrease was less pronounced after 2015 and: a *"decrease occurred across all accident categories except collisions and fires in rolling stock"*. Following the formal vote enquiry and approval of EN 45545, the survey group of JWG was tasked with sorting the unresolved comments and preparing for further revision, as described in subsection 1.1 of this monograph.

EN45545 specifies fire risk levels for different types and categories of rolling stock as well as cases where fire detection and automatic firefighting functions are mandatory for vehicle operation. Nonetheless, it does not contain technical guidelines for the design and validation of such functions, which are included in the other main fire standard mentioned by the TSI, i.e. EN 50553. Extensive work on this issue has also been done in Europe by a "Fire Technology Consortium" established in the early 2000s, initially grouping several entities and companies operating in the field of fire protection, and later on led by recognised testing and assessment bodies operating in Europe (TÜV Sud, Nord, Rheinland). This work has led to the definition and dissemination of the so-called "ARGE Technical Guideline", which is structured into three sections (Fire Detection, Firefighting and Functionalities of Fire Systems in Railway Vehicles) whose objective is to define the "*Minimum requirements and guidelines for qualification of fire protection technology on board of Rolling Stock*". The ARGE guidelines were first released in 2007 (initially only in German) and were later updated in 2009, 2012 and 2018 and translated and disseminated in English. Though not a true standard, the ARGE guidelines have significantly contributed to the definition of the current practice and state-of-the-art in fire prevention and control in rolling stock.

A further evolution has recently been observed in Italy, where a new technical standard was published in 2014 for the application of what is commonly referred to as the "*Specific case Italy*" of the TSI, i.e. an exception to the general rule which foresees the use of common standards throughout the Union. Indeed, due to the specific nature of the Italian railway infrastructure, the Italian ministry of Transport issued the so-called "Decreto Gallerie Ferrotranviarie" [7], published as a Ministerial Decree in Italy on 28 October 2005 and implemented by provisions of section 7.3.2.20 of the European Loc&Pas TSI, in the edition adopted in 2014. As a consequence of the above exception, fixed automatic fire detection systems must be installed in all passenger and train staff areas of trains running in Italy, and *"units of category A and B passenger rolling stock shall be equipped with active Fire Containment and Control Systems (FCCS)"*. Therefore, the UNI 11565 standard, which is largely based on technical work encompassed by ARGE guidelines, must be used as a reference for the design, installation, validation and maintenance of Fire Protection Systems on rolling stock operating in Italy. Issued for the first time in December 2014, this latest standard was updated in June 2016 (second edition) and then in June 2021, with its current edition being the latest development within the framework of the reference standards in Europe.

Notwithstanding this long series of updates and changes, the evolution of the European framework of rolling stock fire standards is still ongoing, with a further revision of EN 45545 now in progress, and with further work foreseen for the harmonisation between EN 45545 and the Loc&Pas TSI. For more detailed information about this process, see subchapter 3.1.1 of this monograph.

3.1.1. Measures for the Protection of Engine Areas on Rolling Stock

The above section outlines the continuously evolving (and rather complex) scenario of European mandatory standards for rolling stock homologation. Still, this issue is made all the more complex because vehicle manufacturers and railway operators always seek more advanced solutions when designing new rolling stock to ensure ever-higher levels of safety and availability for transportation systems, even beyond what is required by mandatory standards.

One of the areas that have seen the most significant effort in recent years is the protection of on-board technical areas. Indeed, statistics of rolling stock fire events have shown that fires originating in those areas cause the largest number of significant incidents, including those that may have more severe consequences for the safety of personnel and operations [3]. More specifically, areas that contain diesel or thermal engines and/or power equipment are recognised as the most critical, both due to their complexity and the large amount of energy that may be released inside them when a technical failure or mishap occurs for any reason.

It is therefore unsurprising that special attention must be devoted to these areas during the vehicle design and homologation process, and that risk mitigation by the use of fire detection and “safety-engineered” automatic firefighting systems have become a widespread practice, even going beyond the basic requirements specified by mandatory rules described in the above section of this paper. The main scope of this section is to analyse and describe the most common techniques aimed at providing the maximum level of safety for a fire protection system, ensuring that life-critical systems behave as needed, even in the event of an unexpected and undesired incident and/or technical failure.

Addressable Fire Detection and Control System Architecture

One of the basic elements for building an advanced and safe instrumented safety system for fire control and containment is using a suitable architecture that may ensure a high level of intrinsic safety in all conditions. An intrinsically safe fire protection system must, on the one hand, ensure centralised collection and processing of information and a link to the train’s centralised TCMS and information system for close integration of comprehensive protection strategies, and on the other, ensure proper communication with many different sensors and actuators located across various vehicle areas and systems to ensure appropriate coverage of all fire events due to expected (and unexpected) failure modes of various types, even when related to external accidental events like collisions, undue interference and arson.

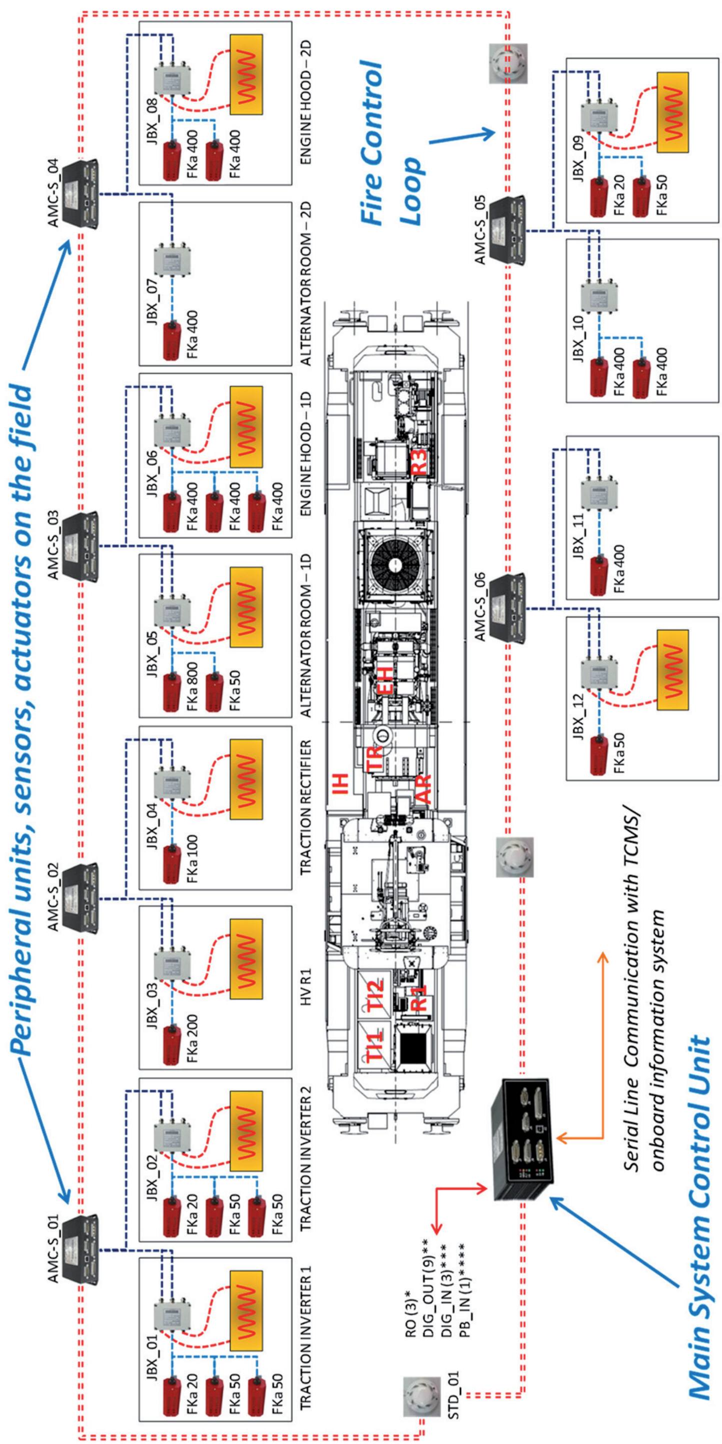

Figure 3.1.1. Sample functional diagram of a modern modular "loop-based" fire control system (source: author's own work)

Considering the above basic needs, a well-designed fire protection system should have a "backbone" in the form of a robust communication link between the system's central control unit and the peripheral sensors and actuators to ensure the proper control of field parameters (for fire detection) and dissemination of commands (for implementing alarm forwarding and fire reaction strategies, such as personnel warning, information transmission, activation of fire barriers and fire extinguishing means, and so on).

According to the above concept, the most advanced and modern fire protection systems are normally based on one or more centralised electronic units (fire control units) which are at the heart of a modular network of sensors and actuators. This network typically takes the form of a "Ring" or a "Loop", which ensures a superior degree of resilience, including in the case of "physical" interruption, which may occur during an incident or undesired/unforeseen collision event (see also section 2.2). A ring-shaped communication loop can be easily implemented using a shielded twisted pair fire-resistant cable and must use physical, electrical, data link and protocol layers that are well-proven and approved for use on rolling stock, as opposite to the more common single-wire DC link used by most commercial systems. The Figure 3.1.1 shows an example of such an intrinsically safe fire protection system installed on a diesel locomotive.

Redundancy of Fire Control System Architecture

The above "ring-shaped" architecture ensures that more than one control unit can rely on the same "fire loop", ensuring redundancy when necessary. As shown in Figure 3.1.2, a redundant system features two control units, both coupled to the main system backbone serial loop and interfaced to all addressable devices linked to them.

In this redundant configuration, one of the control units operates as a "Master", controlling the system's operation, and the other is in "Slave" mode, ready to take over control of the system should the other unit fail. While in standby mode, the "Slave" FDU unit can carry out all the internal tests that are impossible during normal operation without compromising the safety functionalities, including safety relay and watch-dog checks. Thanks to this architecture, the function of Master can be changed periodically to carry out safety tests on both units.

Both units are connected to sensors and actuators installed all over the train through the main system loop, which can be used both for power supply to sensors and for exchanging serial data with both actuator and sensors. Each of the two units can supply power and request data on either of the loop's branches. This ensures the correct operation of the system even when the loop is interrupted for any reason, as illustrated in the picture below (single fault tolerance).

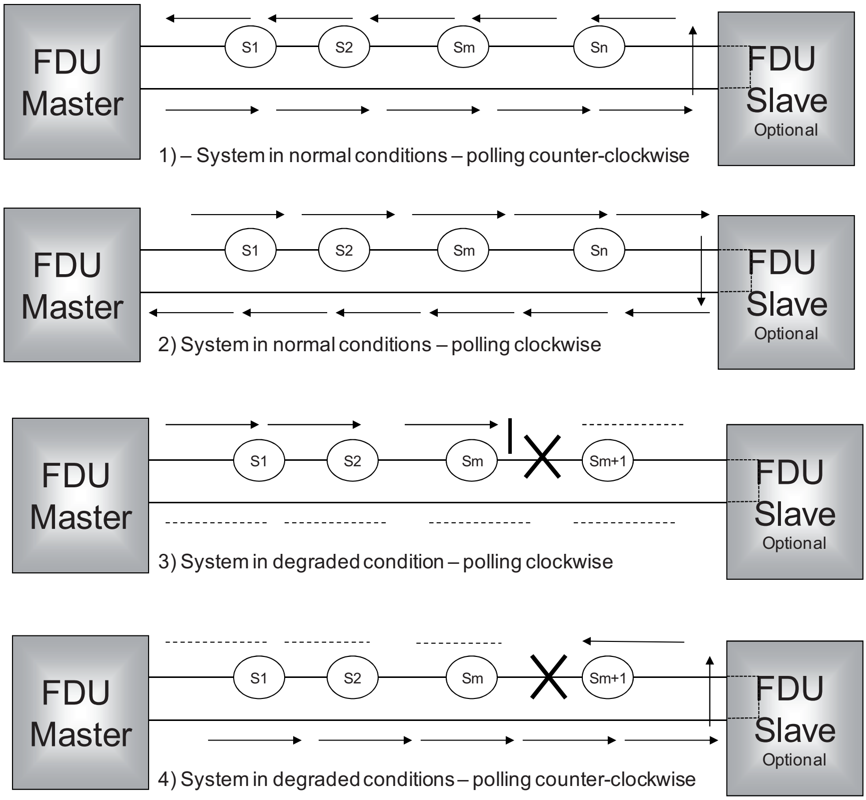

Figure 3.1.2. Advantages of a fully redundant configuration (source: author's own work)

As shown in the picture below, when the loop is interrupted for whatever reason — even in the case of a major interruption along the train (e.g. no connection due to interruption at the interface of two cars) — each unit would poll and control all devices relying on the disconnected branch of the loop. Notably, a fully redundant system configuration lowers the overall probability of a critical fault and may also ensure a redundant link to the vehicle TCMS and/or main communication system, offering increased safety and reliability.

SIL Certification of Fire Detection and Control Systems

One requirement that vehicle manufacturers or transport operators may wish to implement to ensure higher reliability of their Fire Protection Systems is for system functions to have a proper and certified Safety Integrity Level (SIL). A "Safety integrity level" (SIL) is defined as a relative level of risk-reduction provided by a safety function or is used to specify a target level of risk reduction.
In simple terms, SIL is a measurement of performance required for a safety

instrumented function (SIF), implemented using a "Safety Instrumented System". By definition, a "Safety Instrumented System" (SIS) consists of an engineered set of hardware and software controls, especially those used on critical process systems, and therefore, an automatic fire protection system for rolling stock would fall within this classification.

Though the above definitions may seem rather complex to anyone other than a specialised safety engineer, the main underlying concepts of the "level of risk" and "risk reduction" are rather simple: a given risk is characterised by two parameters, i.e. "expected frequency" of the risk and "level of consequence" that can be expected when the risk materialises. An international engineering standard (IEC 61508 [12]) has been expressly issued to define risk levels and categories for the acceptability of specific risk levels; this can be summarised using the following table 3.1.1.

Table 3.1.1. Risk levels and categories for acceptability [12]

Category	Definition	Range (Evt./year)	How many in a fleet of 10.000
Frequent	Many times in system life	$> 10^{-3}$	10-100 /yr.
Probable	Several times in sys. lifetime	10^{-3} to 10^{-4}	1-10 /yr.
Occasional	Once in system lifetime	10^{-4} to 10^{-5}	< 1 /yr.
Remote	Unlikely in system lifetime	10^{-5} to 10^{-6}	< 1 in 10 yrs.
Improbable	Very unlikely to occur	10^{-6} to 10^{-7}	<1 in 100 yrs.
Incredible	Cannot believe that it could occur	$< 10^{-7}$	<1 in 1.000 yrs.

Whenever choosing to reduce a given risk through a "Safety Instrumented System" (SIS), one should perform a risk analysis using recognised methods for the specific transport system and vehicle platform to calculate an "expected level of risk" and determine the extent of risk level reduction that be achieved by safety functionalities (SIF) of the Instrumented System.

The above concept is the main reason why most of the enforced standards for fire protection adopted in Europe (and listed in Chapter 1) do not specify a minimum required SIL. Considering that rail transport implies a significant level of risk for transported passengers, the transport operator and/or vehicle manufacturer should be obliged to perform such a risk analysis to determine the SIL that may be required for their specific application. Nonetheless, this is a complex and difficult task which is not performed formally in most practical cases, and therefore, this concept does not give rise to a requirement for SIL certification in most cases.

Regarding the definition of the new Italian Standard for rolling stock fire protection (UNI 11565) described in Chapter 1 of this paper, the railway safety authority of Italy was aware of this situation when starting the development of the new standard. As such, it conducted an *"a priori"* analysis of the risk level associated with operating passenger trains on the Italian railway network, having regard to its specific characteristics. The authority concluded that, in general, fire risk can be considered "remote", as per the table on the previous page, but may result in multiple casualties if it materialises. Based on this, it requested that a **Safety Integrity Level 2** be required for fire protection systems, which are to be homologated in accordance with the UNI 11565 standard. More specifically, a SIL2 certification is required for the system's general design, software and validation to avoid unwanted system errors, and maximum failure rates corresponding to SIL2 are mandated for system actuation devices operated in "low demand" mode. The Italian standard is therefore unique in this respect, as other railway standards do not contain any specific requirement for SIL certification. It has, to some extent, "paved the way" for defining a more modern concept of a rolling stock fire protection system that is now being increasingly adopted by railway operators and international projects, where SIL certification of safety functions is now required with ever-increasing frequency and extension.

Diversity of Technology and Sensor Redundancy in Critical Areas

One quite useful strategy for fire detection in technical areas is adopting diverse detection technology, which means using various sensor types based on different technologies. This is not the same as using two or more sensors of the same type (which would ensure "redundancy" of detection, but not "diversity"). Applying different technologies or types of devices can make it possible to overcome problems due to "common mode" failures, which is not the case for plain redundancy. This can be easily illustrated by referring to vision systems: if we use a vision system to monitor a given process, having two or more cameras provides a more robust means of detection: vision would be ensured in any case, even if one of the cameras is defective, broken or obstructed for some reason. However, if the field if vision were to be obscured by fog, affecting all cameras in the same way, the vision system's functionality would be compromised. In this case, using one or more infrared cameras in parallel to conventional ones would ensure "diversity", as IR cameras (which are not affected by fog or are affected by it to a lesser extent) would ensure the resilience of the vision system's functionality even in such a case.

In the same way, diversifying technology can help overcome existing problems and/or limitations of a given technology by complementing it with other solutions. Examples of this concept include:

- Using LHD cables for fire detection in technical areas is perhaps the most common and widely disseminated practice, and the success of this solution is due to its high degree of resilience and the ability to be fitted in hard-to-reach spaces at risk of fire, without using many different devices (where only one loop of cable would fit); on the other side, LHDs are rather slow compared to other detection means, and therefore, when a faster detection or early warning functionality is desired, this device can be coupled with other sensor types (e.g. point-type temperature sensors) located in the most critical areas, or with infrared sensors for remote temperature monitoring;
- In some cases, conventional smoke sensors can be used inside technical areas, provided that these areas are not excessively dirty or have too harsh conditions for such sensor types (e.g. high temperatures). On the other hand, such sensors would be more prone to false alarms (e.g. technical issues inside the technical areas, without the presence of fire), and as such, their use may be advisable in cases where early warning is desired in any case, with automatic actuation of firefighting measures taking place based on inputs received by other sensor types (temperature, IR^3 or other sensors).

To illustrate this concept, the Figure 3.1.3 shows infrared tri-band sensors fitted inside the engine bay of a locomotive, monitoring the engine's critical areas, which are also covered by a more extensive loop of LHD cable: this would ensure a faster reaction ability in most cases while maintaining the high reliability of the heat detection cable, which remains unaffected by obstructions and other interference that may occur inside the engine bay.

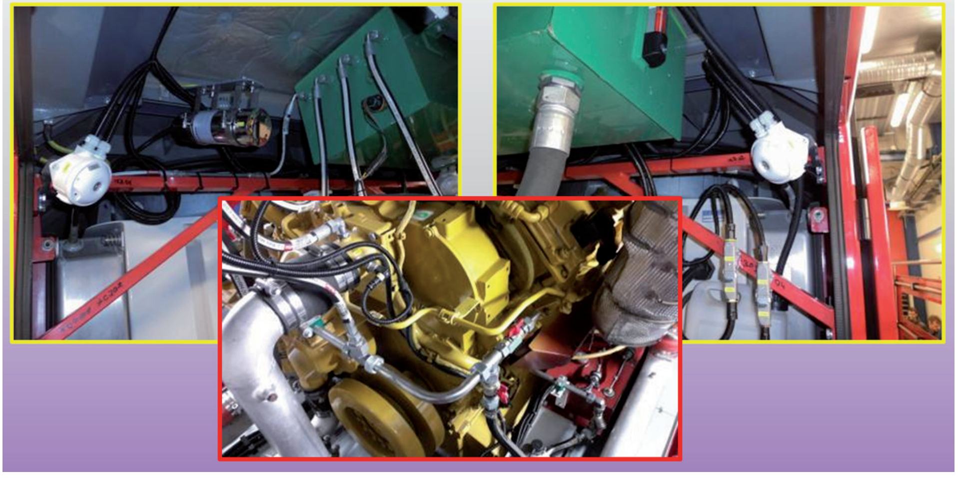

Figure 3.1.3. IR^3 detectors complementing the LHD cables in the engine bay (source: author's own work)

3.1.2. Validation Tests in Technical Areas

Issued in June 2021, the new release of UNI 11565 [11] requires validation tests for technical areas and diesel engines for the Fire Protection System's Detection System and Firefighting/Extinguishing System.

Because of this, verifying compliance with those specific requirements is mandatory for all trains running on the Italian Railways System.

Where validation tests for the Extinguishing System were required under the previous release of UNI 11565:2016 [11], a test for Detection System compliance with EN 50553 [10] has been introduced; however, the criteria have been made more stringent by reducing the detection time from 2 minutes to 1 minute.

Both tests require an accurate analysis of the operating conditions in the room to be protected, a preliminary study of volumes and dimensions, geometry, openings, and leakage areas; the positioning of the sensors and the extinguishing system, as well as all critical issues, must be considered in advance to correctly design the test and to minimise the risk of failing the validation.

Moreover, to properly assess the test result, additional instruments like temperature probes, a thermal imaging camera and an oxygen probe must be used to collect all the data needed to complete a rigorous analysis; even for these instruments, the correct positioning must be previously analysed and considered.

These aspects are discussed in the following paragraphs, with both test types described in detail, focusing on detection effected by LHD cables and an aerosol generator extinguishing system.

Detection Test

Section 10.3.3.1 has been added to the new release of UNI 11565 [11], providing specific requirements for Detection Systems installed in diesel engine technical rooms:

> *Validation tests shall be performed following the CEI EN 50553, and it must be proved that the Detection system is able to detect fires within 1 minute from the ignition of flame in all operating conditions.*

This introduces very strict requirements and new problems in terms of the design and execution of the validation test, such that have never existed before.

Once the test environment has been designed, reproducing all relevant aspects of the as-installed conditions, including a mock-up representing the engine volume and dimensions, alternator and all essential equipment inside the technical room, the ventilation must be analysed and simulated as well.

In the case under study, a forced ventilation system is present; it cannot be stopped in case of fire because it is powered by the rotation of the alternator itself, which draws air from its room into the engine room.

This aspect must be simulated (using ventilators) with the correct air flow and, of course, it is an operating condition that must be considered when determining the dimensions of the firefighting system and designing the validation test itself.

The LHD cable must be positioned closer than in the real-world application and the fire sources must be located at the critical points where an actual fire may occur.

For this reason, a preliminary study of possible causes of fires and critical points in terms of temperature is mandatory for Detection System validation and efficiency tests.

Once the possible fire origin points have been identified, the fire source's location during the test must be selected.

Section 6.5.2.1 of EN 50553 specifies the "Alternative Burner" as an ignition source, as defined in Annex A.2 of ISO 9705 [15] (see Figure 3.1.4), using natural grade propane (95% purity, see ISO 9705 [13], section 6.3).

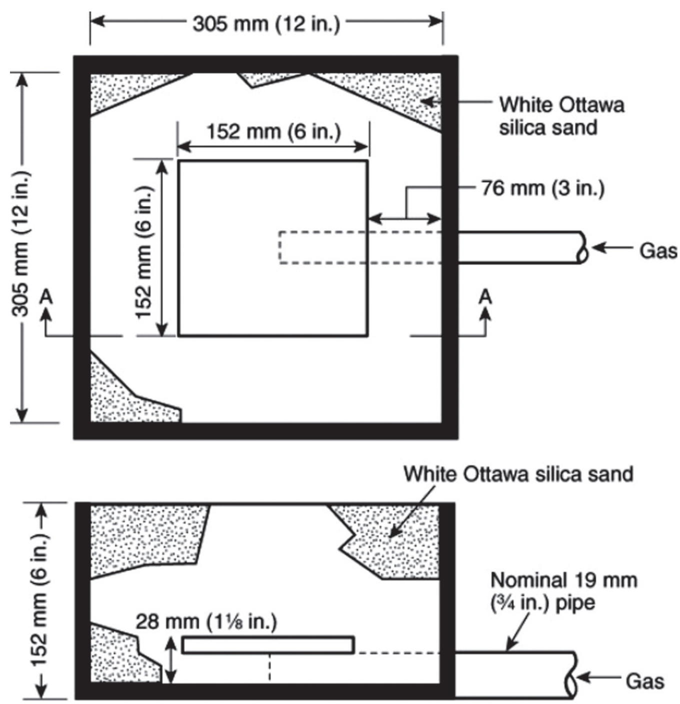

Figure 3.1.4. Alternative Burner [13]

The fire scenario is a Type 2, as defined in section 3.1.4 of EN 50553, i.e.: a "*fire which has the power vs. time profile of Ignition source 5 of CEN/TS 45545-1; 75 kW for 2 minutes followed by 150 kW for 8 min*".

Due to the time limit of 1 minute under UNI 11565, the burner's Heat Release Rate must be limited to 75 kW for the duration of the test.

This HRR value can be obtained with a combustible material flow rate of ~1.6 g/s, as set by a certified mass flow controller.

Because of factors like the dimensions of the Alternative Burner and the height of its flame, the position of the fire source must be carefully considered, including in terms of the physical space available inside the engine room and the need to try and prevent the LHD's direct contact with flames; different positioning must be tested and results thoroughly examined.

At the time of writing of this paper, only preliminary analysis, implementation and testing of the fire scenario and preparation of the testing environment (mock-up included) have been conducted. No tests involving the NoBo's assessment have been completed yet; however, this activity is expected to be wrapped up within a few months, and no critical issues have been detected so far.

Fire Extinguishing System Test (Aerosol Generators)

As for Detection, the first step in designing such a test is the preliminary analysis of the volume to protect.

The dimensions and geometry of the technical room, the shapes and volumes of the equipment inside it, as well as any openings, leakage areas and ventilation, must be considered and evaluated to reproduce a "realistic" mock-up and simulate all the relevant aspects of the operating conditions.

Once the mock-up has been developed, the positioning of aerosol generators, already defined in terms of extinguishing mass and numbers by preliminary calculation, is vital for the success of the test and, ultimately, for the efficiency and effectiveness of the firefighting system itself.

Specifically for diesel engine rooms, sections 10.4.2.2 and 10.4.2.3 of UNI 11565:2021 [11] require a compliance test (in static conditions) using the "pool fire" scenario described in the EN 50553 [10]; moreover, the extinguishing time after the pre-burn (60 seconds per EN 50553 6.5.3.2) may not exceed 120 seconds, followed by a no-reignition time of 20 minutes from the start of the first discharge.

The fire source shall be:
– 12 litres of liquid, comprising 4 litres of water on which is floated 8 litres of n-heptane;
– The tray shall be circular with a surface area of 0.2 m² and a depth of 150 mm. It shall be made from steel of 2 mm thickness.

The reference standards contain no requirements concerning the position of the fire source(s) but, as for the Detection Tests, identifying possible fire breakout locations is mandatory for a correct validation of the adopted solution; the fire source positions during the test must be defined, analysing critical points and root causes of fires inside the relevant technical rooms.

For this reason, a location under the engine mock-up and partially "hidden" by it has been chosen for the main diesel engine room scenario (pool fire) under EN 50553.

The intention is to simulate a fire due to a leakage of combustible material from the engine to the room's bottom; the pool fire must be partially uncovered to avoid smothering the flame before the activation of the Extinguishing System.

A pool fire with such dimensions and combustible material quantity releases an enormous heat power (~380 kW) and generates fairly high flames. Such a fire is anything but easy to put out and the Extinguishing System, with aerosol generators in this case, must have the proper dimensions and be correctly positioned to be effective and extinguish the flame in the required time.

The Extinguishing System must be manually activated at the defined time (after a 60-second pre-burn) and discharge effectiveness must be evaluated after 120 seconds.

Though not required by the relevant standards, secondary fire sources were analysed and used to test and validate the Extinguishing System's performance in the presence of additional fires in different positions all over the protected area.

A preliminary study of possible fire breakout locations was performed as well, and such additional fires were then used.

Smaller "pools" with n-heptane were positioned as shown in Figure 1 below; they are useful in reproducing fires due to combustible material leakage in different situations than what was considered for the main scenario (e.g. between the engine's banks) or due to failures in the alternator room.

The extinguishing of those additional fire sources during the first discharge and within 120 seconds is a further confirmation of the System's effectiveness across the entire protected area.

Then, as the final fire scenario, further additional fire sources were used to test the no-reignition time of 20 minutes after the first discharge.

To simulate reignitions, a scenario in compliance with EN 15276 [14] section A.7.1.2.2 and ISO 15779 [15] section D.7.1.1.2 was designed; it involved the use of n-heptane-filled cans with an internal diameter of 80 mm and a height of 100/110 mm, equipped with a remote reignition mechanism consisting of a pilot flame fed by propane gas and ignited by a remotely activated piezoelectric igniter.

These fire sources were activated at a predefined time, depending on the tested application and the operating conditions.

In the case of large openings or consistent leakage areas in the real-world application causing a significant dispersion of the aerosol, additional discharges can be considered.

Even in this case, reignition fires are useful in testing the efficiency of the extinguishing system and its validation in terms of hold time (20 minutes after the first discharge).

To correctly assess the test results, the following data must be recorded:

- Initial test environment temperature and oxygen level;
- First discharge duration;

- Fire scenario extinction time, calculated from the end of the discharge (by reading the data from the installed thermocouples and using the thermal imaging camera);
- Oxygen level at the time of discharge;
- Reignition of the cans;
- Duration of the secondary discharges;
- Reignition source (can) extinction time, calculated from the end of the secondary discharges, by reading the data from the installed thermocouples and using the thermal imaging camera.

If the test results comply with all requirements of EN 50553 [10] and UNI 11565 [11] the Validation Test is passed.

Figure 3.1.5 shows the locations of different fire scenarios and temperature and oxygen probes for an already completed diesel engine locomotive Validation Test.

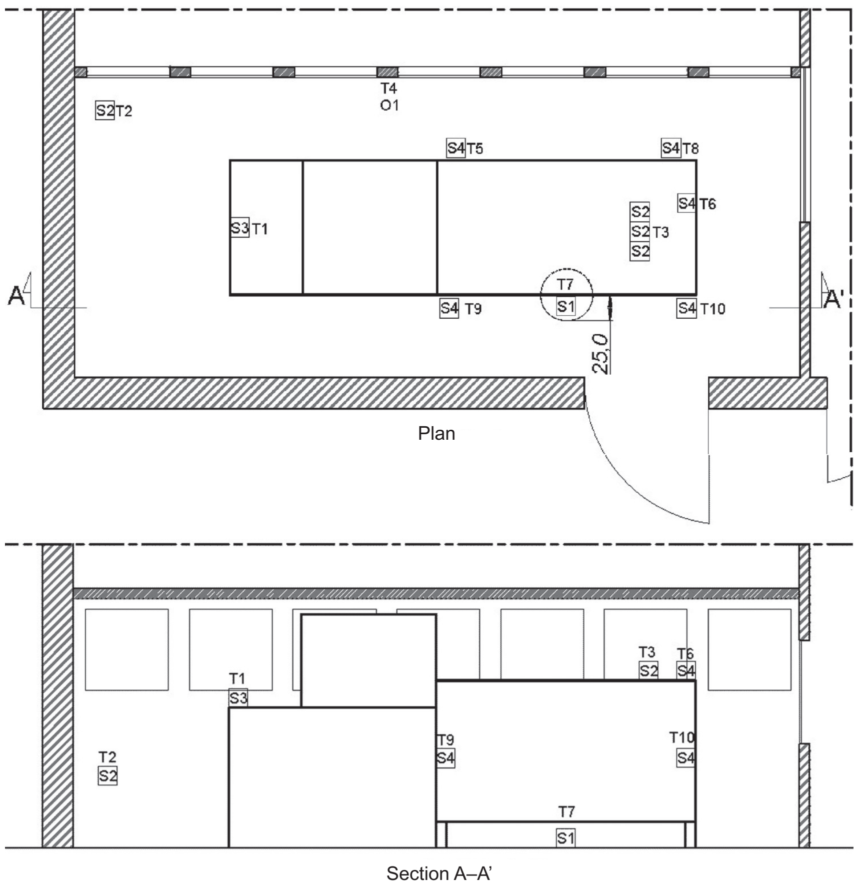

Figure 3.1.5. Positions of the secondary fire sources and probes. S1 is the main fire scenario (pool fire), S2÷S4 are the secondary fire scenarios, T1÷T10 are the temperature probes, O1 is the oxygen probe (source: author's own work)

3.1.3. Conclusions

Fire effects are some of the most harmful conditions that Rolling Stock may experience throughout its service life.

Recent years have improvements in the development of protection methods and standards to prevent potential fire-related disasters in railway transport, which was accompanied by the proliferation of new and more stringent standards and practices.

At the same time, rapid developments in technology have increased the demand for modern, innovative fire protection systems that must be closely integrated with train monitoring and diagnostic tools and adaptive fire reaction strategies to ensure safety and service continuity in increasingly multimodal transport scenarios.

Innovative fire protection systems have been designed to handle the increased risk posed by Thermal Engines and High-Power Equipment on several platforms. This has been followed by the evolution of protection strategies along with the development of new European Standards like EN 50553 [10] and EN 45545 [9], as well as the most recent Italian Standard UNI 11565 [11].

Several solutions have been introduced for the protection of critical areas, including redundant and multimodal detection strategies in engine rooms, various firefighting technologies, certification of fire solutions for Safety Integrity Levels up to SIL2, close integration with onboard communication and monitoring systems, condition-based maintenance strategies and purposeful fire reaction procedures at the vehicle level, which all increase protection effectiveness.

This article presented some examples of protection strategies and solutions adopted for the protection of technical areas housing combustion engines or power equipment on board rolling stock.

It also outlined the strategy adopted by the authors to ensure compliance with the requirements of the most recent standards.

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3.2. Assessment of Electrical Equipment in the Field of Rolling Stock Fire Safety

The unified basic requirements for rolling stock contained in the Technical Specifications for Interoperability (LOC&PAS TSI 1302/14) also apply to fire protection. Per section 4.2.10.2.1 of the LOC&PAS TSI, any non-metallic material used on rolling stock must meet the requirements of EN 45545-2. On this basis, we know that the fire protection requirements also apply to electrical and electronic devices intended for rolling stock. The design, verification and testing of electronic equipment on board rolling stock is standardised in detail by EN 50155. This standard also refers to EN 45545-2 and EN 45545-5 under "Requirements for fire behaviour": EN 45545-2:2020 only covers electronic equipment in Table 2 — Requirements for listed products, in items EL9 and EL10. EN 45545-5:2013 + A1:2015 specifies requirements only for electrical equipment, without explicitly referencing electronic equipment. Consequently, the application of the EN 45545-2 and EN 45545-5 standards to electronic equipment intended for installation on board trains enables different interpretations of these standards.

3.2.1. Standard References

According to section 4.2.10.2.1 of the LOC&PAS TSI, each non-metallic material used on rolling stock must meet the requirements of EN 45545-2. Therefore, electrical and electrotechnical equipment and its elements in passenger rolling stock must meet the fire safety requirements (e.g. this includes monitoring and information systems for passengers, on-board control and signalling systems, supply line elements and high power devices, heating devices and others). Fire protection requirements for materials, per the LOC&PAS TSI [8], must be met through devices belonging to the "Command and Signalling" subsystem (per the CCS TSI). The need for on-board CCS devices to meet the relevant fire requirements is also confirmed in section 4.2.3.1.1 of the SRT TSI [9](a document relating to safety in railway tunnels). Additionally, the new edition of the EN 50155:2020 [3] standard dedicated to electronic equipment on rolling stock contains expanded guidelines for the verification and testing of electronic equipment in the field of fire protection. It states that the EN 45545-2 [1] and EN 45545-5 [2] standards should be used to protect against the spread of fire.

3.2.2. General Approach for Evaluation

To determine the approach to assessing the compliance of devices with the requirements of the EN 45545-2 [1] and EN 45545-5 [2] standards, different cases of implementing such products in various lifecycle phases, e.g. design, manufacturing, integration/installation and maintenance, should be considered. Therefore, it is vital to examine those aspects that require guidance on the interpretation of the requirements. A methodical approach to conformity assessment for electronic equipment on board rolling stock must be provided. The equivalence of the tests performed according to UL 94 Ed 6 [6] (V-0 test) and EN 60695-11-10 [7] should also be analysed.

Equipment manufacturers generally do not have any guidance on the actual on-board installation, so assessing compliance with fire protection requirements is considered a multi-step process. This multi-stage process should include:

- Conformity assessment of systems as independent elements (e.g. printed circuit boards, electrical wires, device housings — specified elements);
- An assessment of the technical cabinet intended for the assembly of such equipment, which may affect the assessment of the elements contained therein;
- An assessment of the device's conformity, considering its location and configuration in the vehicle: a stand-alone device, an element of a rack cabinet or a device placed in a technical cabinet.

3.2.3. Compliance Evaluation

Compliance Evaluation of the Standalone Elements

Classified products are considered as listed products. In this case, it is very simple to determine the requirements. Table 2 of EN 45545-2 [1] contains the relevant requirements and the defined test methods for them.

The main classified products used in technical equipment are PCBs, cables and housing (where it is non-metallic). Most of the components are in contact with the PCB only, which normally is compliant with Table 2, EL9, of EN 45545-2 [1].

Classified products may also be considered as unclassified ones. For example, cables which are listed products are subject to requirements under R15 or R16 (table 5 of EN 45545-2). However, for applications where the mass and area thresholds given in section 4.3 of EN 45545-2 are not exceeded, it is possible to consider them as non-listed products. Therefore, the requirements depend on the mass and area of non-metal components used in the given cable. These thresholds and dependencies are described in section 4.3 of EN 45545-2 [1] and are referred to as grouping rules.

Many materials used in electrical equipment are categorised as V0 class according to UL 94 [6]. This refers to the declaration of conformity of the component manufacturer or the "Yellow Card" information.

Technical Cabinet Compliance Evaluation

In general, this involves evaluating all requirements applicable to the equipment installed in technical cabinets. However, where equipment is fitted inside a technical cabinet which:

- complies with integrity criterion E10 per EN 45545-1 [4] and EN 45545-3 [5] and has an enclosed volume of ≤ 2 m^3,
- complies with integrity criterion E15 and insulation criterion I15 for surfaces adjacent to passenger areas and staff areas and integrity criterion E15 for other surfaces based on the definitions in EN 45545-1 [4], with no volume limitations,
- is protected by an automatic fire detection and fire extinguishing system,
- contains only mechanical or low-power electrical equipment and the cabinet walls are closed and made of aluminium, steel or glass. The enclosed volume is ≤ 0.1 m^3. Covered openings (e.g. by connectors or switches) are acceptable,
- has walls made of aluminium or steel,
- has an enclosed volume of 0.5 m^3. For any individual surface of the cabinet, the total area of all openings in that surface must be less than 1/1000 of the nominal surface area,

it may also be considered as unclassified and additional factors do not need to be assessed.

3.2.4. General Rules

The general rules apply to all types of materials. These rules are the starting point for any analysis of non-metal components used on rolling stock. The first step is to determine the exposed area. If it is greater than 0.2 m^2 and the given component is a listed (classified) product, requirements from Table 2 of EN 45545-2 [1] are applied. If not, R1 for interior or R7 for exterior use are required. Where the exposed area is less than 0.2 m^2 and the mass does not exceed 10 g with no contact with another non-tested product, no requirements are applied. Otherwise, grouping rules should be applied. Figure 3.2.1 below illustrates the general rules.

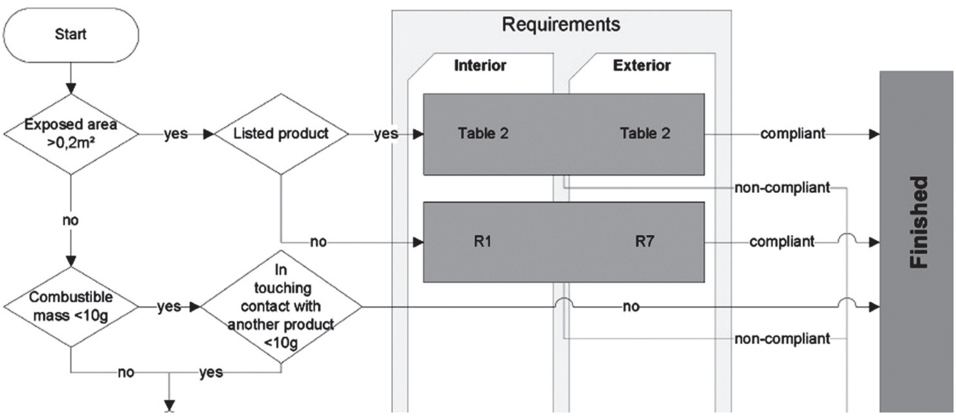

Figure 3.2.1. Graphic representation of the general rules for tested materials [1]

Classified Products

Classified products are listed in Table 2 of EN 45545-2 [1]. The requirements are labelled with the letter "R" (from R1 to R28 in EN 45545-2:2020) and refer to Table 5 [1]. Table 5 contains the test methods for each requirement. Figures 3.2.2 and 3.2.3 below present examples applicable to products classified with requirements R1 and R26.

Non-Listed Materials

All products that are not listed in Table 2 [1] should be considered as non-listed ones and be tested according to Table 3 [1], as shown in Figure 3.2.4. The applicable requirements depend on the exposed area and location on board rolling stock.

Table 2 — Requirements of listed products

Product No	Name	Details	Requirement
IN	**Interiors**		
IN1A	Interior vertical surfaces	Interior components (structure and covering) such as side walls, front/end walls, partitions, room dividers, flaps, boxes, hoods, louvres. Interior doors, interior lining of the front/end wall doors and external doors. Windows (including plastics and glazing) Insulation material and interior surface of body shell. Kitchen interior surfaces (except those of kitchen equipment).	R1

Table 5 — Material requirement sets

Requirement set (used for)	Test method reference	Parameter and unit	Maximum or Minimum	HL1	HL2	HL3
R1 (IN1A; IN1B; IN1D; IN1E; IN4; IN5; IN6A; IN7; IN8; IN9B; IN11; IN12A; IN12B; IN14; EX4A; F5)	T02 ISO 5658-2	*CFE* kWm^{-2}	Minimum	20 a	20 a	20 a
	T03.01 ISO 5660-1: 50 kWm^{-2}	*MARHE* kWm^{-2}	Maximum	-	90	60
	T10.01 EN ISO 5659-2: 50 kWm^{-2}	$D_S(4)$ dimensionless	Maximum	600	300	150
	T10.02 EN ISO 5659-2: 50 kWm^{-2}	*VOF4* min	Maximum	1 200	600	300
	T11.01 EN 17084 Method 1 50 kWm^{-2}	CIT_G dimensionless	Maximum	1,2	0,9	0,75

Figure 3.2.2. A product classified as IN1A with R1 requirements [1]

EL10	**Low power electro technical and electronic products**	**Examples include low power circuit breakers, overload relays, contactors, contactor relay, switches, control or signalling switches, terminals, fuses**	**R26**

R26 (EL9, EL10)	**T17** **EN 60695-11-10** **or equivalent**	**Vertical small flame test**	**Minimum**	**V0**	**V0**	**V0**

Figure 3.2.3. A product classified as EL10 with R26 requirements [1]

Exposed area	Location	Requirement set in Table 5
> 0,2 m^2	interior	R1
> 0,2 m^2	exterior	R7
≤ 0,2 m^2	interior	R22
≤ 0,2 m^2	exterior	R23

Figure 3.2.4. Requirements for non-listed products [1]

3.2.5. Grouping Rules

As already mentioned, components not meeting the thresholds given in section 4.3 [1] may be considered as non-listed products and grouping rules can be applied. For components with a mass below 10 g and no contact with other components non-compliant with [1], no requirements apply. If the mass is greater or other components are in contact, the relevant components must be considered as a group and their masses summed. The following grouping rules should be used for the assessed group:

- Rule 1: group mass ≤ 100 g for interior and ≤ 400 g for exterior — no requirements apply.
- Rule 2: group mass ≤ 500 g for interior and ≤ 2000 g for exterior — one group product should be tested according to R24 [1].
- Rule 3: group mass above that in Rule 2 — one group product should be tested according to Table 3 [1].

If the tested product complies with the requirements according to the applied rule, it should not be considered in further assessment. The remaining products in the group must be assessed starting with the first rule again until no more requirements apply to the assessed group.

General grouping rules apply in any case. To prevent situations where the sum of the non-metallic parts exceeds the thresholds that require certification, it is good practice to maximise the presence of certified materials in the design, especially those present in significant number, mass and concentration, especially for a subrack-based solution, as per Figure 3.2.5.

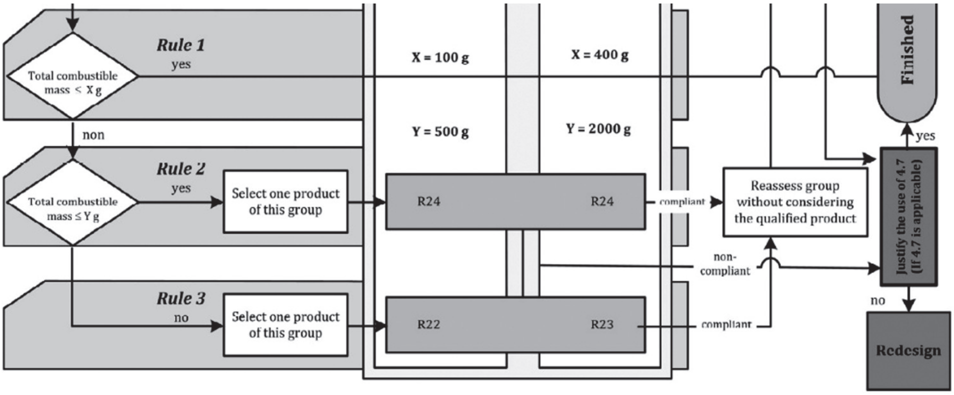

Figure 3.2.5. Grouping rules diagram for components with an exposed area of ≤ 0,2 m^2 [1]

3.2.6. Section 4.7

There are cases when section 4.7 of EN 45545-2:2020 [1] can be invoked for a certain electronic component and/or subsystem element In such a case, it is advisable to collect, as far as possible, information from the manufacturer that is relevant to the materials and structure of the component/element in question. Such information must then be used to draw up a report to demonstrate that:

- there are no other solutions available to fulfil the requested function,
- the chosen solution contributes to the requested level of functional safety; the impact on the passengers in terms of smoke and fire is acceptable or sufficiently mitigated,
- it is to be noted that the data sheets reporting the characteristics of the electronic components cannot be considered a test report; however, they are useful to demonstrate the reason why they were chosen in the design phase.

3.2.7. Case Study

Figure 3.2.6 shows the procedure for assessing a printed circuit board.

3.2.8. Conclusions

The fire safety requirements for electrical and electronic devices are some of the elements subject to verification when assessing rail vehicles. The documents describing the approach to the assessment of electrical devices define the applicable methodology in a very general manner. Therefore, it is crucial to establish a detailed document that outlines the standard approach in the assessment of such devices.

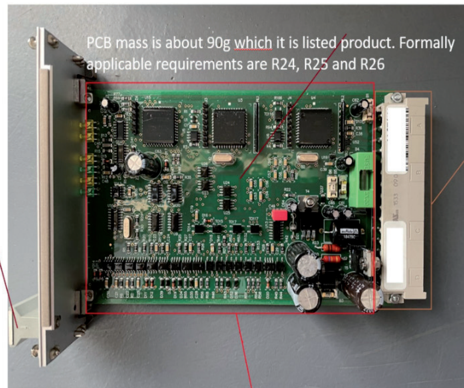

Figure 3.2.6. Example of evaluating a printed circuit board (source: authors' own work)

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4 Fires, Design, Rescue and Firefighting Exercises

Systematic development in the design of rolling stock units requires regular training in rescue and fire-fighting operations in vehicles and rail infrastructure. The effectiveness and safety of carrying out such actions requires anticipating various scenarios, including those involving vehicles powered by alternative fuel sources. The above requires knowledge of the design of a number of vehicles in operation, sometimes very different from each other, as well as the potential sources of ignition that may occur.

The first part of this chapter presents current regulations and design fires that have occurred or are needed to assess designs for fire safety of rolling stock, stations and railway tunnels.

The second subchapter discusses the principles of planning, designing and conducting emergency exercises. Included is a process for identifying the most likely events for which exercises would be useful, as well as how often they should be conducted and guidelines for assessing them.

The third subsection presents the American approach to historic passenger trains in order to ensure their fire safety. In the United States, passenger train safety standards are addressed in federal regulations published by the Federal Railroad Administration (FRA). Title 49 of the Code of Federal Regulations, Part 238, (49 CFR 238) addresses Passenger Equipment Safety Standards and Title 49 of the Code of Federal Regulations, Part 239 (49 CFR 239) addresses Emergency Preparedness. Part 238 is very prescriptive in its specifications for Fire Safety (238.103), especially with regard to the test methods and performance criteria for the flammability and smoke emission characteristics of materials used in passenger cars and locomotives. While the application of these specifications is relatively easy to achieve in the purchase of new passenger equipment, applying these specifications to heritage equipment presents unique challenges. Fortunately, in cases where interior finishes and components cannot be easily replaced with new compliant materials, the railroad may apply remedial actions. This fire protection engineering activity requires significant engineering judgement and creativity. This paper presents how a reasonable level of fire and life safety was achieved in a 73-year-old passenger carriage by applying remedial actions. The paper takes the form of a USA case study and looks at the fire safety challenges through the lens of a railroad operator.

4.1. Review of Design Fires for Railway Fire Safety Assessment, and for Railways Infrastructure Management

Fire safety assessment of railway rolling stock or railway infrastructure such as stations and tunnels requires proper scenarios. These scenarios depend on the regulation as well as the safety objectives.

For rolling stock, scenarios stated in EN 45545-1 Appendix A 0 may be used to define source terms of heat release rate and toxic gases emissions relevant to demonstrate compliance of rolling stock to essential requirements of EU directives 2008/57/EC [7] and now 2016/797/EC [8]. The latter is a new approach directive and several ways of assessment are possible depending on the authority, NoBo and level of compliance to prescriptive exigences [9].

For infrastructure, source terms of heat and smoke used are defined for the fire safety of stations and are nationally regulated. A proper approach to such smoke modelling may be required for people's evacuation, as well as structural fire engineering. The same applies to tunnels, where a fire scenario and source terms of heat and smoke are needed for the determination of the fire resistance degree of the infrastructure (e.g. Tunnels TSI [6]) and evacuation of people.

This section focusses on regulation, safety objectives and design fires established or needed to assess fire safety design of rolling stock, stations and infrastructure like railway tunnels.

4.1.1. Review of design fires in railways

The standard ISO 16733-1:2015 [11] gives the following definition of a design fire: "*quantitative description of assumed fire characteristics within a design fire scenario*". Additionally, this definition includes the following Note 1: "*Typically an idealised description of the variation with time of important fire variables, such as heat release rate and toxic species yields, along with other important input data for modelling such as the fire load density*".

On the other hand, the applicable requirements include Interoperability Directive 2016/797/EC [8] (Figure 4.1.1). It is a new approach directive with explicit objectives. The TSIs describe the essential objectives at the sub-system level (e.g. rolling stock, tunnels, etc) and a prescriptive approach is warranted. Objectives are deemed to be satisfied when compliant, e.g. with EN 45545-2 [10] in the case of rolling stock.

Nevertheless, several ways of demonstrating compliance are permissible and equally acceptable as prescriptive ones presented to the authorities.

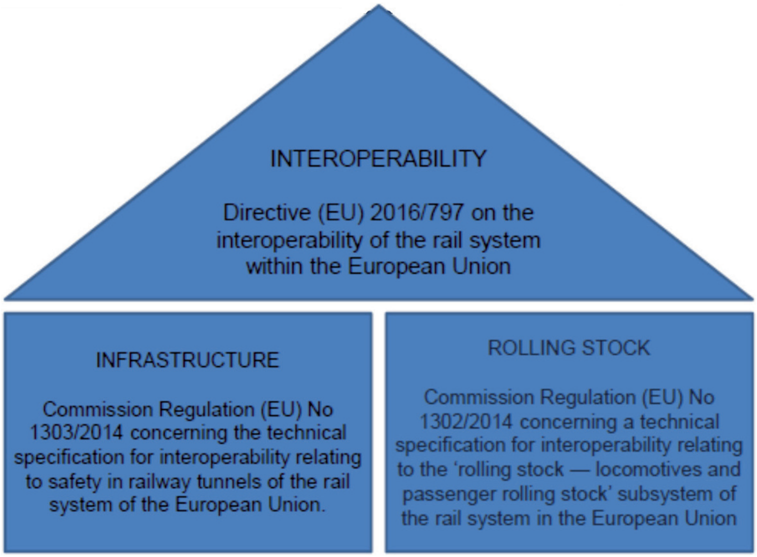

Figure 4.1.1. Interoperability Regulation (source: authors' own work)

4.1.2. Design Fires and Design Fire Scenarios for the Application of the LOC&PAS TSI

The essential requirements are given in section 4.2.10.1 of the LOC&PAS TSI [5]:

> *"Rolling stock shall be designed such that it protects passengers and on-board staff in case of hazard fire on board and to allow an effective evacuation and rescue in case of emergencies. This is deemed to be fulfilled by complying with the requirements of this TSI."*

The above requirements concern such things as:

- Material requirements (a reference to the 2013 version of EN 45545-2, as well as the more recent 2020 version with a transition period [10]);
- Fire detection systems;
- Fire containment and control systems for passenger rolling stock.

However, the following reference scenarios were used in EN 45545-2 [10]:

- Those established during the FIRESTARR study, 1997–2001,
  - based on feedback from railways operators prior to 1997,
  - based on rolling stock compliant with previous national standards,
  - introduction of arson fires,
- Those refined within JWG CEN TC256/CENELEC TC9X, 2002–2003,
- The defined criteria and heat flux exposure for prescriptive tests,

- Those published in EN 45545-1 Appendix A [9] — ignition models 1 to 5 (not explicitly).

Yet, these are not Design Fire Scenarios but ignition scenarios. Indeed, Design Fire Scenarios must be associated with a probability of occurrence and include a contribution from train materials (See ISO 16733-1 [11] and ISO 16733-2 [12]) (Figures 4.1.2–4.1.3). A significant contribution to the design of fire scenarios was obtained as part of the European TRANSFEU project implemented in 2009–2012, particularly: WP4 to WP6: Definition of Fire Safety Engineering methodology for railway rolling stock compliant with EN 45545-2 (*Final report available on the EU website* [13]).

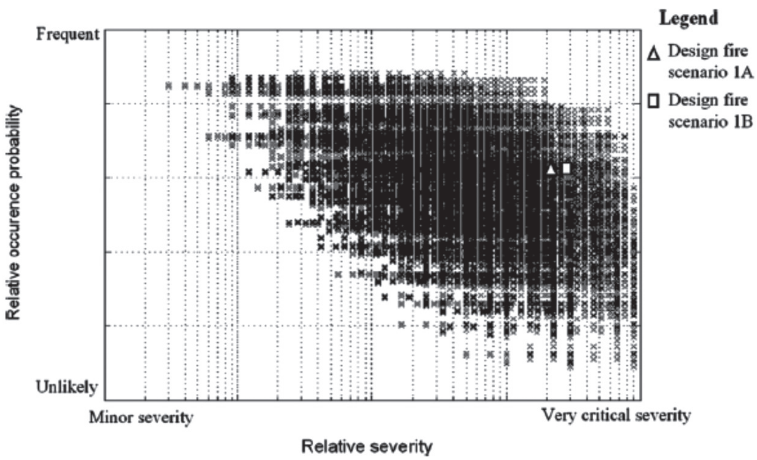

Figure 4.1.2. Example of DESIGN FIRE SCENARIOS using input from TRANSFEU [2]

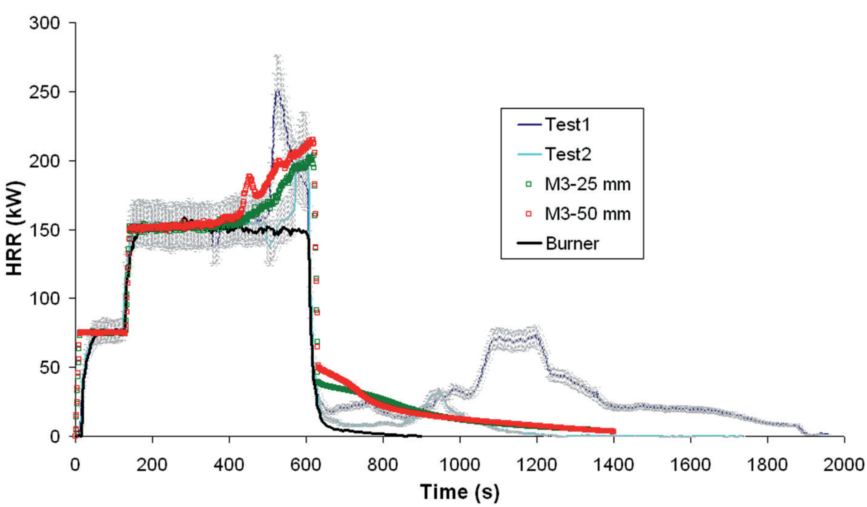

Figure 4.1.3. Example of DESIGN FIRE SCENARIOS using input from TRANSFEU [3, 4]

Below are some examples from another research programme (Figures 4.1.4 and 4.1.5).

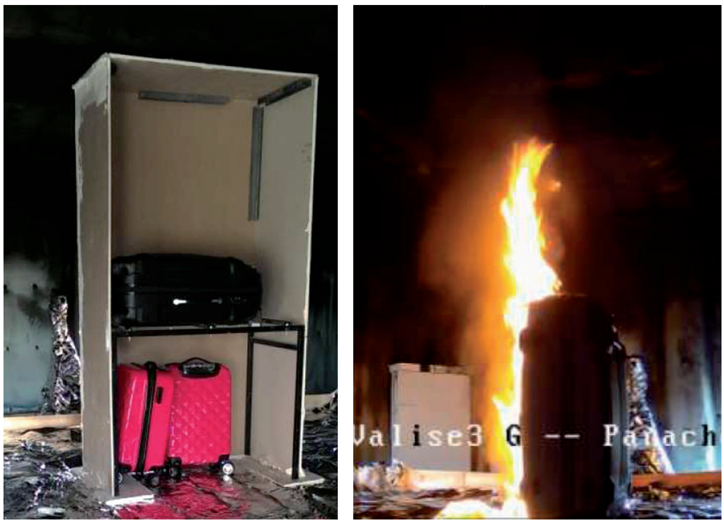

Figure 4.1.4. Luggage fires, Re(h)strain research programme [1]

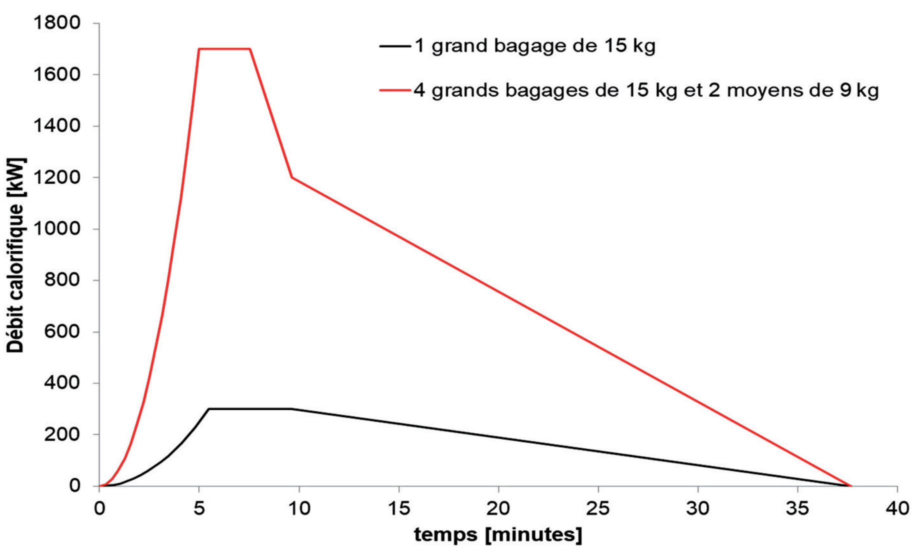

Figure 4.1.5. Luggage fire test results, Re(h)strain research programme [1]

4.1.3. Design Fires and Design Fire Scenarios for the Application of the SRT TSI

In respect of fire safety requirements, four categories of rolling stock are defined and specified in the SRT TSI [6]:

- Category A passenger rolling stock (including passenger locomotive);
- Category B passenger rolling stock (including passenger locomotive);
- Freight locomotive, and self-propelling unit designed to carry other payload than passengers (mail, freight, infrastructure inspection vehicle, etc.);
- OTMs.

Examples of Fire Cases

Below are examples of events that have occurred in various types of rail vehicles in recent years in France:

- High-speed train fire: Pont de Veyle, 10 January 2009 — transformer oil fire; estimated power of fire: 3–5 MW (Figure 4.1.6);
- Freight car fire: Belfort, 6 April 2010 — 6 new cars involved simultaneously; estimated heat release: about 40 MW at peak; however good accessibility made it possible to extinguish the fire in only 30 min (Figure 4.1.7);
- Freight car fire: Valenciennes, 25 March 2022 — tyre fire at the station (Figure 4.1.8).

Figure 4.1.6. High-speed train fire, Pont de Veyle, 10 January 2009 (source: property of authors)

Figure 4.1.7. Freight car fire, Belfort, 6 April 2010 (source: property of authors)

Figure 4.1.8. Freight car fire, Valenciennes, 25 March 2022 (source: property of authors)

Examples of Design Fires for Infrastructure

Example 1. Transformer + Power System Fires (Figure 4.1.9 and 4.1.10)

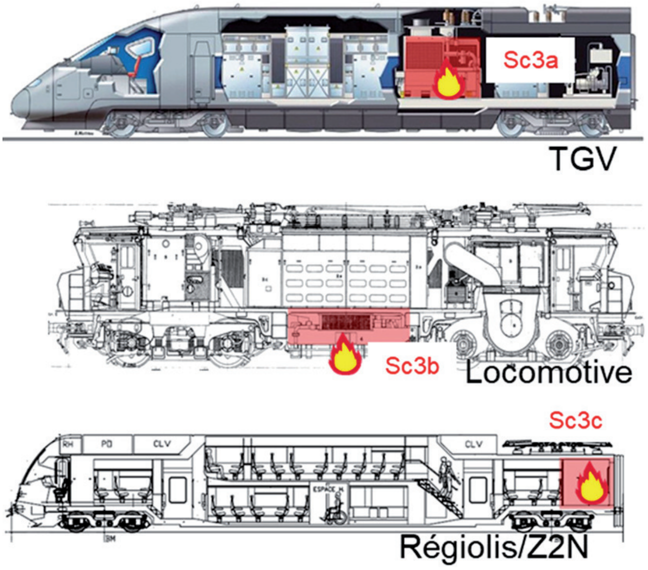

Figure 4.1.9. Example locations of fires in different trains (source: authors' own work)

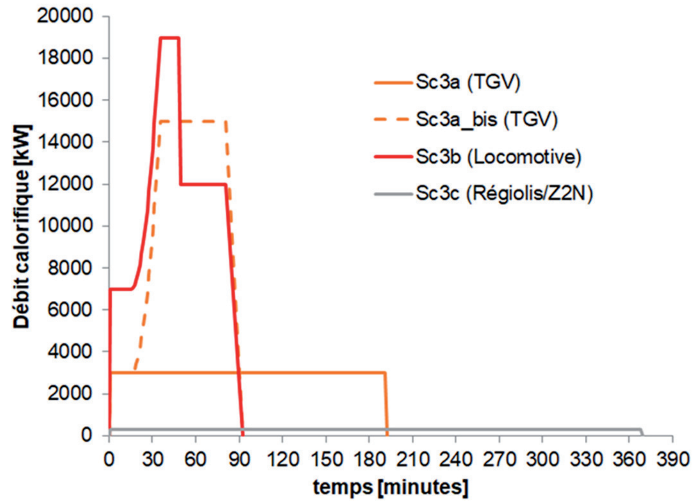

Figure 4.1.10. Fire Heat Release for different trains (source: authors' own work)

Example 2. **Diesel Engine Fires** (Figure 4.1.11 and 4.1.12)

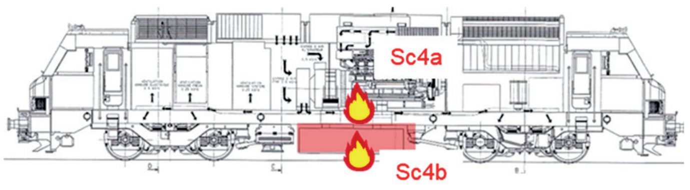

Figure 4.1.11. Diesel engine fires [.]

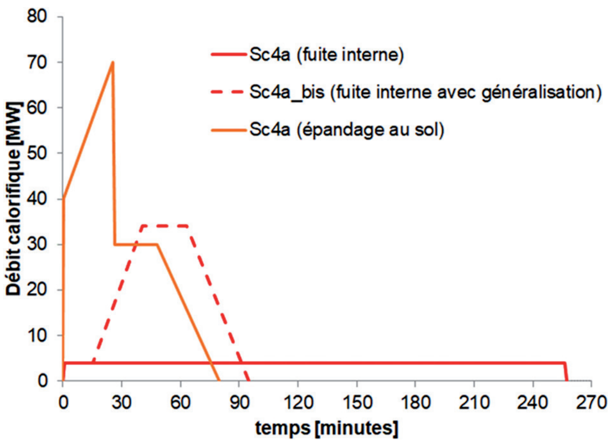

Figure 4.1.12. Fire Heat Release for diesel engine fires (source: authors' own work)

Example 3. Urban Trains — Rooftop HVAC Cabinet Fires (Figure 4.1.13 and 4.1.14)

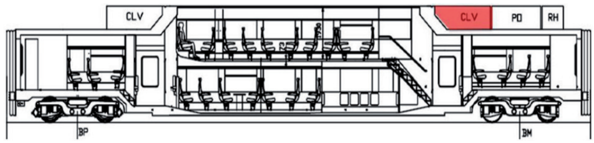

Figure 4.1.13. Urban trains — Rooftop HVAC cabinet fires (source: authors' own work)

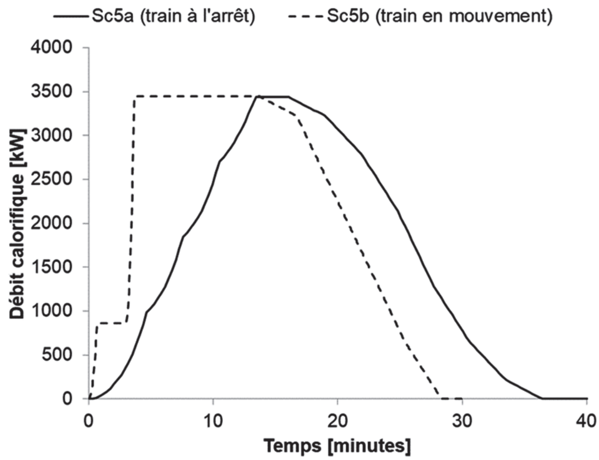

Figure 4.1.14. Fire Heat Release for urban train rooftop HVAC cabinet fires (source: authors' own work)

Example 4. Interior Fires Ignited by Luggage Fires (Figure 4.1.15)

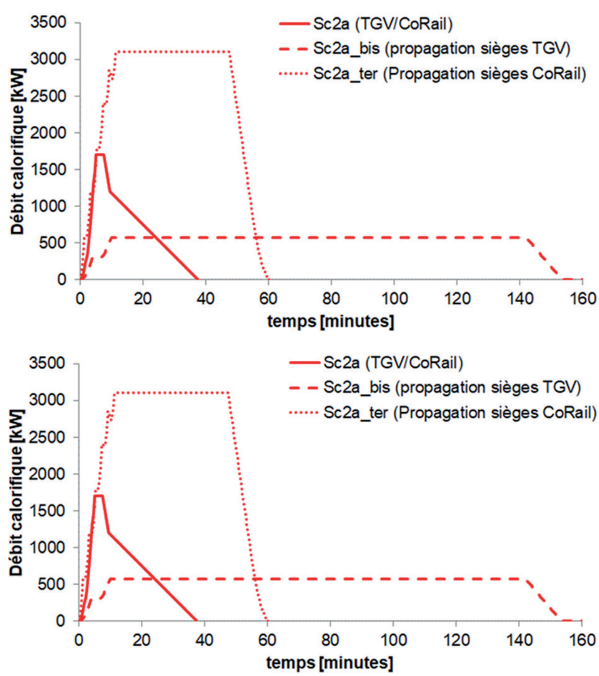

Figure 4.1.15. Fire Heat Release for interior fires ignited by luggage fires in passenger trains in France (source: authors' own work)

4.1.4. Conclusions

The examples presented show the complexity of the phenomenon of fire. At the same time, they make us aware that the systematic development of railways in terms of vehicles and their power sources, as well as infrastructure, including tunnels and stations, requires many issues to be considered when predicting future threats. These include:

- a high correlation between tunnel ventilation and design fire,
- the problem of tunnel/station interactions,
- the evolving use of stations,
- the anticipated technological hazards:
  - battery-powered trains and trams,
  - hydrogen trains.

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[2] Camillo A., Guillaume E., Rogaume T., Allard A., Didieux F. *Risk analysis of fire and evacuation events in the European Railway Transport Network*. Fire Safety Journal, vol. 60:25–36, 2013.

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[4] Guillaume E., Camillo A., Rogaume T. *Application and Limitations of a Method Based on Pyrolysis Models to Simulate Railway Rolling Stock Fire Scenarios*. Fire Technology, Vol. 50(2), pp. 317–348, 2014.

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[5] Commission Regulation (EU) No 1302/2014 of 18 November 2014 concerning a technical specification for interoperability relating to the 'rolling stock — locomotives and passenger rolling stock' subsystem of the rail system in the European Union (LOC&PAS TSI).

[6] Commission Regulation (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to safety in railway tunnels of the rail system of the European Union (SRT TSI).

[7] Directive 2008/57/EC of the European Parliament and of the Council of 17 June 2008 on the interoperability of the rail system within the Community .

[8] Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union.

[9] EN 45545-1. Railway Applications — Fire Protection on Railway Vehicles — Part 1: General.

[10] EN 45545-2. Railway Applications — Fire Protection on Railway Vehicles — Part 2: Requirements for Fire Behaviour of Materials and Components.

[11] ISO 16733-1:2015. Fire Safety Engineering — Selection of Design Fire Scenarios and Design Fires — Part 1: Selection of Design Fire Scenarios.

[12] ISO/TS 16733-2:2021. Fire Safety Engineering — Selection of Design Fire Scenarios and Design Fires — Part 2: Design Fires.

Websites

[13] https://cordis.europa.eu/project/id/233786/reporting.

4.2. The Planning, Conduct and Evaluation of Emergency Exercises In Rail Transport

While rail transport is officially the second safest mode of transport behind aviation (measured as fatalities per billion passenger kilometres), there is evidence to suggest that when accidents occur they have the potential to result in very large numbers of fatalities and severely injured passengers. These are, quite often, "once in a generation".

That is why it is essential to plan, prepare and rehearse. High levels of command and control are required to quickly bring order and safely resolve the incident. Without practice, lessons learned are not passed on.

According to EU Regulation 402/2013/EU [1], Common Safety Method — practitioners are encouraged to anticipate the hazards and risks — and design them out.

Four layers of defence are mentioned:

- Prevention;
- Mitigation;
- Evacuation; and,
- Rescue.

The RST TSI [2] describes the following roles of the Fire and Rescue Services:

The definition of the role of the rescue services is a matter for the Relevant National Authority. Incidents are classified as either "hot" or "cold".

In a "hot" incident type:

- Try to rescue people unable to reach a safe area;
- Provide initial medical support to evacuees;
- Fight a fire insofar as required to protect themselves and people caught in the accident;
- Conduct evacuation from safe areas inside the tunnel to open air.

In a "cold" incident type:

- Provide initial help to people with critical injuries;
- Free trapped people;
- Evacuate people.

Effective command and control of rescue and firefighting operations is very important to quickly end incidents and accidents.

The examples of exercises presented in this section are based on the author's experience.

4.2.1. Emergency Exercises

An emergency exercise is a simulation of an emergency situation, accident or incident.

Exercises have 3 main purposes:

- to validate plans (validation),
- to develop staff competencies and provide practice in carrying out specific roles in the plans (training),
- to test well-established procedures (testing).

Why It Is Important to Hold Exercises

Planning for emergencies cannot be considered reliable until it is exercised and has proved to be workable, especially since false confidence may be placed in the integrity of a written plan.

Generally, participants in exercises should have an awareness of their roles and be reasonably comfortable with them, before they are subject to the stresses of an exercise. Exercising is not to catch people out. It tests procedures, not people. If staff are under-prepared, they may blame the plan, when they should blame their lack of preparation and training. An important aim of an exercise should be to make people feel more comfortable in their roles and to build morale.

4.2.2. Types of Exercises

There are three main types of exercises:

- discussion-based,
- table top,
- live.

A fourth category combines elements of the other three.

The choice of which one to adopt depends on what the purpose of the exercise is. It is also a question of lead-in time and available resources.

Discussion-based (seminar-style) exercises

Discussion-based exercises are the cheapest to run and easiest to prepare. They can be used at the policy formulation stage as a "talk-through" of how to finalise the plan. More often, they are based on a completed plan and are used to develop awareness about the plan through discussion. In this respect, they are often used for training purposes.

Table top exercises — also known as floor plan exercises

Table top exercises are based on simulation, not necessarily literally around a table top. Usually, they involve a realistic scenario and a time line, which may be real-time or may speed time up.

Usually, table tops are run in a single room, or in a series of linked rooms which simulate the divisions between responders who need to communicate and be co-ordinated. The players are expected to know the plan and they are invited to test how the plan works as the scenario unfolds.

This type of exercise is particularly useful for validation purposes, particularly for exploring weaknesses in procedures. Table-top exercises are relatively cheap to run, except in the use of staff time. They demand careful preparation.

Live exercises

Live exercises are a live rehearsal for implementing a plan. Such exercises are particularly useful for testing logistics, communications and physical capabilities.

They also make excellent training events from the point of view of experiential learning, helping participants develop confidence in their skills and providing experience of what it would be like to use the plan's procedures in a real event. Where the latter purposes are, in fact, the main objective of the exercise, then it is, essentially, a training exercise or practice drilLive exercises are expensive to set up on the day and demand the most extensive preparation. The expense of live exercises may be reduced by limiting the number of players and by scheduling them to fall within working hours to avoid overtime payments. It may also be possible to rearrange training to coincide with the exercise. However, some exercises have to be held outside normal hours for safety or commercial reasons.

For live exercises which involve large numbers, it may be possible to use some players to act as evacuees and hold a rest centre exercise thus providing training for a wider pool of agencies.

4.2.3. Emergency Planning Process

Exercises should be regarded as integral parts of the emergency planning process — not isolated options. It is important that emergency plans have been prepared and the appropriate staff trained in their roles before an exercise is planned. After any exercise, the plan should be reviewed and amended from lessons learned before the process starts again.

4.2.4. Exercise Planning

Most exercises are time-consuming and cannot be undertaken frequently. Therefore, every opportunity should be given to all appropriate agencies to take part when a plan is tested. Managers, executives, chief officers, etc., must be kept informed of plans and progress as their support is vital for success. The group needs to allocate sufficient time (which may mean several months prior to the event) to plan the exercise thoroughly.

Ideally, those involved in planning the exercise should not participate directly. They are better used as Umpires or Observers. If possible, and particularly for small organisations, help should be sought from neighbouring areas or organisations with similar operations.

4.2.5. Aim/Objectives

The aim and objectives of the exercise, including clear outcomes, need to be established at the outset and should ideally be the first item on the planning group's agenda. The overall aim of the exercise should be agreed upon by the senior management of all participating agencies and be based around the question "what are we hoping to achieve by the exercise as a whole?".

4.2.6. Scenario

The scenario needs to be realistic to ensure that participants will take the exercise seriously. The exercise should also have a realistic timescale.

The scenario should include:

- day, date and time, and
- nature of the incident (consistent with exercise location).

Other considerations might be:

- weather conditions including wind speed and direction, visibility,
- traffic conditions,
- progression of the incident (e.g. different phases), and people involved (e.g. young, elderly etc.).

Always remember, however, that planning based on detailed assumptions regarding a likely future scenario may be too inflexible to adapt to the unforeseen. Adopt a willingness to be flexible.

4.2.7. Exercise Location

Whatever type of exercise is to be held the planning group should visit the location — at a similar time/day as the exercise — to ensure that it is appropriate. They should also seek written permission from parties which have a claim to an area and inform any potential users that it may be out of bounds on a certain date.

The remainder of this chapter will concentrate on a Live Exercise.

The selection of a suitable site for an exercise is of crucial importance. For generic-type major disaster exercises, e.g. air or rail crash, selecting a suitable site should be undertaken in the early stages of exercise planning. As the site needs to be acceptable to all participating agencies, several options may need to be explored depending on the scenario. The location must be safe, secure and with reasonable access for vehicles and personnel. Owners of the site (for example, possibly Network Rail or London Underground) should be fully aware of and, if possible, participate in the exercise.

4.2.8. Exercise Base

The need for an "exercise base" arises for live exercises, sometimes for control post exercises, and is particularly helpful for large-scale exercises. A suitable building, preferably in the ownership of one of the participating agencies, should be selected close to the exercise site. It can then act as an assembly point for „exercise directors", observers etc. where briefing can be given and casualties, if used, can be made up. Ample car parking should be provided.

If the exercise base is further than walking distance from the site, then consider providing minibus transport. Bear in mind that live multi-agency exercises attract many vehicles and it would be helpful to ensure that non-essential vehicles at the site are kept to a minimum.

4.2.9. Safety at the Exercise

The safety of personnel during a live exercise is of paramount importance. Exercise participants may not be familiar with the location and control may be needed to ensure that players are kept within the confines of the exercise area.

Before a live exercise, a safety audit should be completed to ensure that structures are safe and no unseen dangers are present on the site (e.g. asbestos in old buildings or transport). A safety officer must attend the exercise to ensure that all participants comply with the safety requirements and do not place themselves, or others, in danger. At complex exercises, or where conditions are particularly hazardous, each participating organisation may need its own safety officer. The exercise must not be seen as a reason not to comply with health and safety requirements.

4.2.10. Welfare

Consideration should be given to welfare arrangements during exercises. Welfare needs may vary depending on the type, timing and duration of the exercise. There will be a need to provide refreshments, changing, washing and toilet facilities before, during or after the event. The use of casualties adds realism to exercises but their welfare needs to be taken into account. Exercise "casualties" should not be placed in unsuitable conditions e.g. cold, wet or hard surfaces without appropriate care. Invariably the length of time envisaged for the activity turns out to be much longer. An area which is warm and dry should be available.

4.2.11. Codewords

Exercises may be given a codename which should then be mandatory as a prefix to all messages — verbal or written — during the exercise. The group must take care that the codeword chosen is phonetically distinct from other key words that are used in communications. Neither should such words be used for other purposes in emergency response operations (e.g. Gold, Silver, Bronze).

4.2.12. Logging and Recording

An important means of communication, particularly after a real incident, will be contemporaneous records and logs. These can be particularly important in subsequent public enquiries. In exercise, those taking part should understand the importance of keeping an accurate log of actions and decisions. Exercise planners should not assume that players will bring their organisations' logging practices to the event — even where they exist.

4.2.13. Media Participation

Dealing with the media is a major part of responding to any incident and therefore should be practised as often as possible. The exercise planners could deploy student journalists, the Central Office of Information or reporters from local papers to test the different agencies' responses to the media. For major exercises, a representative from the national media should be invited to attend. Exercise press conferences and interviews can be used to test the knowledge of the combined response.

4.2.14. Media Coverage

The media might arrive, unplanned, to cover the exercise and arrangements must be in place for this possibility. Public relations staff should be allocated to keep the media informed during the exercise. Designate a good viewing point and useful locations for photo-opportunities.

4.2.15. Briefings

The type and number of briefings will depend on the exercise's aim. As a general principle, each agency's representative on the exercise planning group should take responsibility for briefing those of their staff who are involved in the exercise. Further briefing may be required on arrival at the place of deployment. Particular attention needs to be paid to volunteers.

Further briefing will be required for additional exercise directors and observers. It is advantageous to give these briefings at the exercise base before it begins.

4.2.16. Pre-Exercise Final Arrangements

These are the responsibilities of the members of the exercise planning group so that all possible measures have been taken to ensure that the exercise itself is not compromised by poor planning and organisation.

4.2.17. Live Exercises

- Participants should be briefed prior to the exercise.
- The scene is set with casualties made up and in place.
- Observers briefed, in position and suitably identifiable (tabards).
- Exercise directors briefed, in position and suitably identifiable (tabards).
- First aid support (if necessary) in place and clearly identifiable.
- External groups briefed and in place.

- Welfare arrangements (refreshments, temporary toilets etc.) in place.
- Media arrangements made.
- Communication checks complete.

The participation of the focus for the exercise — e.g. a train, tunnel or station — has been guaranteed or an alternative scenario has been prepared to discount its absence.

It should be remembered, particularly in live exercises, that although the exercise on site has been completed other elements may need to continue for some time, e.g. control rooms, casualty bureau, media etc.

4.2.18. Debriefing

A review of the responses to an exercise by the emergency services and agencies giving assistance is essential. This provides an opportunity to evaluate efficiency, to learn from experience gained and also offers a source of information to assist in future planning, training and exercising.

This process can be best achieved by a series of debriefings at all levels within all agencies involved and concluding with a multi-agency debrief. Hot de-briefs (those which take place immediately after the event) can be a useful way of capturing instant reactions which may not be revealed by the cold de-brief (that which takes place after an interval). All actions identified by the debrief should be taken forward by a nominated person/agency and given a timescale.

Organisations may wish to consider appointing a neutral debrief co-ordinator. A non-threatening atmosphere must be created so that people are not afraid to be honest about their experiences and problems.

4.2.19. Single Service Debriefing

The methods of debriefing personnel involved in a major incident may vary within each service. It will, however, be beneficial to debriefing if consideration is given to the following:

Debrief as soon after the exercise as is practicable. Everyone involved, including personnel remote from the area of operations (e.g. control room staff) should be allowed to contribute to debriefing at some stage. Consider the need for additional debriefing sessions for personnel involved in specific or specialist operations.

NB: Recordings made at the exercise, particularly video recordings/photographs, along with written reports will assist in debriefings.

4.2.20. Multi-Agency Debriefing

The debriefing process should culminate in a multi-agency forum which includes not only the emergency services but also any other agency which may have assisted in the overall response. Each service must be represented by personnel actually involved in operations, as it will be necessary to give first-hand accounts of events.

Depending on the scale and nature of the exercise it may be advantageous to hold joint debriefings for specific levels of command, e.g. Incident Control Team (Tactical level) and/or for personnel deployed on tasks requiring multi-agency involvement. Such meetings should, of course, be a pre-cursor to the final multi-agency debriefing and should add to its content.

NB: Facts emerging from the debriefings should be documented and problems identified. Lessons learned should be shared with all who may be required to respond to major incidents even if they did not participate. Training needs — individual, organisational and multi-agency — should be identified. Consider sharing "lessons learned" with a wide audience.

4.2.21. Exercise Report

A major multi-agency exercise can be both costly and time-consuming to arrange and undertake. It is particularly useful, therefore, to produce an exercise report after the debrief. This should be well presented and brief so that the busiest manager has no excuse not to read it. The report should cover the aim, objectives, scenario, the planning process and both positive and negative observations from the exercise concluding in recommendations for the future. It is also important that the recommendations are acted upon and a follow-up report prepared no later than 6 months after the publication of the Exercise Report noting what action has been taken and what is planned.

Exercise Checklist
This can vary, depending on the scenario and exercise type.

4.2.22. Example of EUR Exercise

EUR took two years to plan and nine months to analyse to ensure that its evaluation was comprehensive and fully evidence-based. The initial bid for EU funding was made in June 2014 and the bid's success was confirmed later that year. A project "kick-off" meeting was held in Brussels in early 2015 involving EU officials and representatives from each of the exercise beneficiaries.

EUR involved 2,500 volunteer casualties over four days; each had an individual profile and was "tracked" during the exercise through "the journey" that affected persons will take following a major incident. The exercise was facilitated by 300 staff representing all the organisations that had been involved in EUR's planning. Each of the four days was run following a structured "daily rhythm", with exercise activity taking place between 10:00 a.m. and 8:00 p.m.

To ensure continuity, situation reports were devised overnight by facilitation staff in relation to past and predicted events and these were used to brief oncoming participants the following day.

Figure 4.2.1. Members of EU and UK USAR and EUR project team at Woolwich Barracks [3]

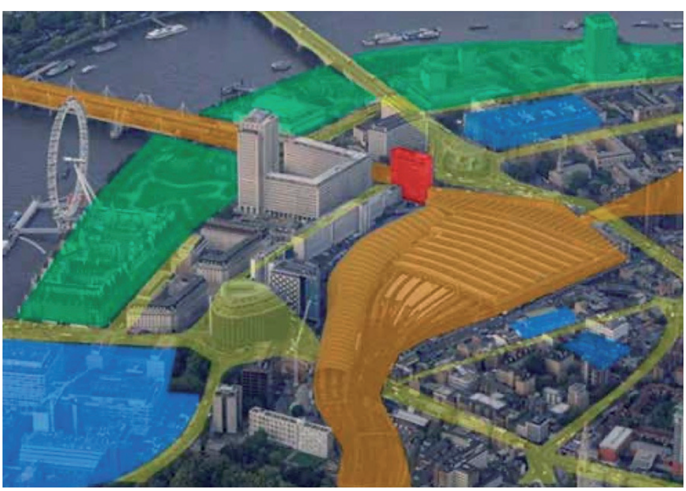

Figure 4.2.2. EUR's centrepiece — the rescue scene [3]

Figure 4.2.3. Overview of the rescue scene [3]

EUR's centrepiece was the rescue scene. The scenario was based on a building collapse in a central London main line train station and to enhance the realism of the strategic (command post) element Waterloo was chosen as the incident location. The strategic (command post) element interacted with the live site in real time and was further developed via 1,700 "injects". These depicted the wider effects of the emergency, such as those impacting transport, health and the community.

Scenario

- The exercise was based on a major building collapse at "Waterloo station", key parts of which were re-created in a disused power station.
- Waterloo was chosen because it is a central London mainline and underground train station. The scenario was focused on eight underground carriages which had been covered in thousands of tonnes of rubble following a building collapse.
- Responders accessed the scene through a highly realistic station entrance which led them to the train carriages via a labyrinth of tunnels, concourses, staircases and platforms. These had been specially constructed on-site, mainly using timber and scaffolding.
- The scenario provided a very dynamic and authentic incident for responders at the scene and also generated a myriad of consequential strategic London and UK impacts, such as those affecting transport, health, businesses and the wider community.

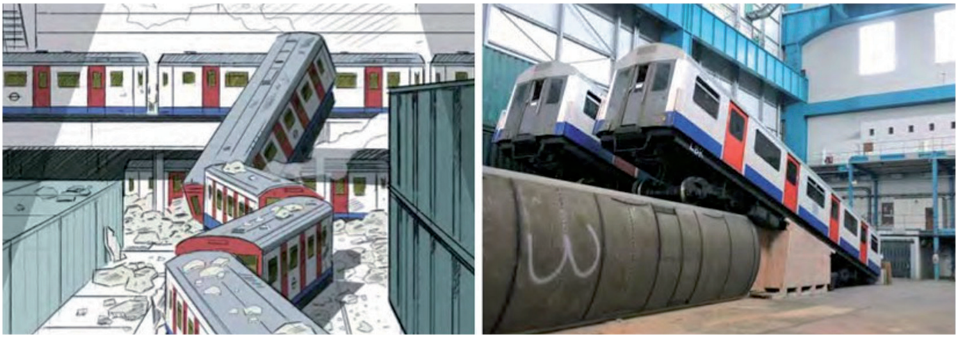

Figure 4.2.4. Left: An artist's impression of the rescue scene. Right: The rescue scene under construction in November 2015 [3]

Figure 4.2.5. Members of the national USAR team building one of the station tunnels [3]

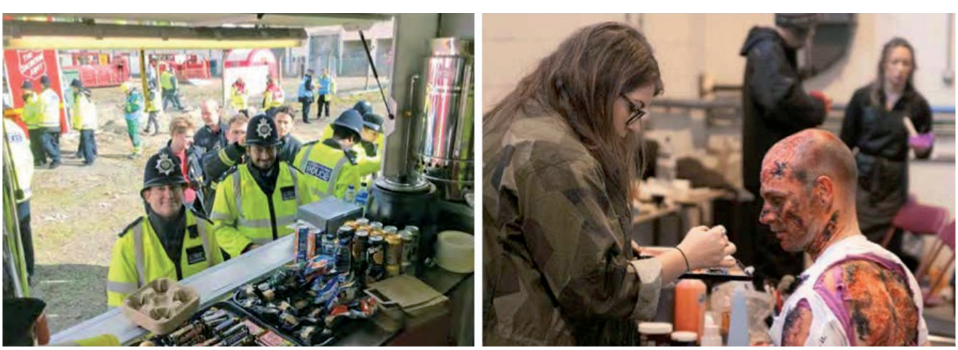

Figure 4.2.6. Left: The Salvation Army feeding responders. Right: Casualty volunteers being made up by students from Rotherham College [3]

Figure 4.2.7. Left: briefing casualty volunteers. Right: volunteer feeding area [3]

Figure 4.2.8. Building collapse at "Waterloo station" [3]

Exercise Timescales

The exercise was run over 4 days, from 29 February–3 March 2016. The live play elements of the exercise took place between 10:00 a.m. and 8:00 p.m. daily with simulated play outside of these hours.

The Venue and its Consequences

The live element of EUR was staged in a former turbine hall at a recently decommissioned power station in Dartford and within the London M25 orbital motorway.

Figure 4.2.9. The Didcot Power Station boiler house was set for demolition when it collapsed [4]

Very sadly, there was a major incident with fatalities at an actual turbine hall of a similar design that was being decommissioned. That incident occurred on 23 February 2016, under one week before EUR began and one day before the full dress rehearsal. This was a sombre reminder of the intensity of operations required at such catastrophic events.

The decision had to be made to go/no-go. It was made with sensitivity, consideration and conscious humility that EUR should go ahead.

How Were Lessons Learned Shared?

- The visitor programme enabled 545 people to observe the exercise including the UK Home Office Permanent Secretary, London's current mayor and the EU Director-General responsible for humanitarian aid and civil protection.
- Two conferences were organised to promote and reflect on the outcomes of EUR.

4.2.23. Conclusions

Proper planning, design and execution of major contingency exercises should take into account the most likely events for which the exercises would be useful. The planning process should also take into account the frequency of exercises and route maps, as well as the criteria for assessing exercises and directions for their improvement.

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[4] www.Thames Valley Police.

4.3. Remedial Actions to Assure Fire and Life Safety in Heritage Passenger Cars — A USA Case Study

The Catalpa Falls Group, LLC (CFG) is a Texas Limited Liability Company (USA), founded in 2003, and is headquartered in San Antonio, Texas. The company's principal base of operation is in Philadelphia, Pennsylvania (USA). CFG owns several heritage rail carriages and provides historical rail excursions through its subsidiary, Executive Rail. CFG is a for-profit, private passenger rail car operator, targeting high-end customers who enjoy a superior level of customer service on heritage rail cars built in the 1940s and 1950s (Figure 4.3.1 and 4.3.2). Executive Rail offers its customers the opportunity to "travel back" to the "golden age of American passenger trains".

Figure 4.3.1. Executive Rail's on-board staff (source: property of author)

Figure 4.3.2. A typical gourmet meal service (source: property of author)

4.3.1. Executive Rail's Operation on Amtrak Trains and Routes

Executive Rail (ER) operates its passenger carriages within Amtrak trains and travels Amtrak's nationwide USA network. Executive Rail launched its Amtrak service on 19 July 2019 and offers both single "day trips" as well as longer overnight excursions. ER meets the most stringent Amtrak mechanical, safety, and operational standards, as ER's carriages are certified to travel on Amtrak's Northeast Corridor (NEC), and enter Amtrak's Penn Station, New York City (Figure 4.3.3).

Figure 4.3.3. The *Catalpa Falls,* underground in Amtrak's Penn Station, New York City (source: property of author)

Executive Rail experiences are custom-curated, with some journeys taking place over a 3-day "long weekend", such as a trip from New York City, New York to Pittsburgh, Pennsylvania and return (Figure 4.3.4). As an example, the New York to Pittsburgh excursion covers 444 miles (715 km) at a scheduled transit time of 9 hours each way.

Figure 4.3.4. The *Catalpa Falls* passing through Bryn Mawr, Pennsylvania westbound on its trip to Pittsburgh, Pennsylvania from New York City (source: property of author)

Other Executive Rail journeys can be much longer in duration. At present, Executive Rail's longest duration excursion has lasted 8 days, departing New York

City and travelling to New Orleans, Louisiana (Figure 4.3.5). The travel distance of this trip was 1377 miles (2216 km) with a scheduled transit time of 33 hours in each direction.

Figure 4.3.5. The *Catalpa Falls* en route through the snow from New Orleans to New York City on the rear of Amtrak's train number 20, the *Crescent.* Photographed just north of Washington, D.C. on 30 January 2022 (source: property of author)

The importance of understanding Executive Rail's business model cannot be understated. Executive Rail's "brand" is to offer a memorable transportation and hospitality product to high-budget travellers. ER's approach to this market, is to utilise vintage (heritage) rail carriages that were used in the "golden age of rail travel in America", refurbish them to the highest practicable standards, and then provide a luxury, white glove, culinary and hospitality service during the trip. To simply buy new passenger rail carriages would negate the nostalgic component of the "mid-twentieth century train travel experience".

The Catalpa Falls Group, LLC's ownership and management took fire and life safety under serious consideration during the rebuilding of the rail carriage *Catalpa Falls*. This paper, presented as a case study, explains the management considerations that were used to guide the development and execution of the fire and life safety philosophy that was implemented during the rebuilding of the *Catalpa Falls.*

4.3.2. Regulatory Review

CFG management began developing its fire and life safety design philosophy by first looking to the United States federal regulations and examining the [then] current requirements for fire and life safety as applied to passenger rail equipment. Guidance was found in Passenger Equipment Safety Standards, 49 CFR § 238

(1999–2019) https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II/part-238 [1] (Figure 4.3.6).

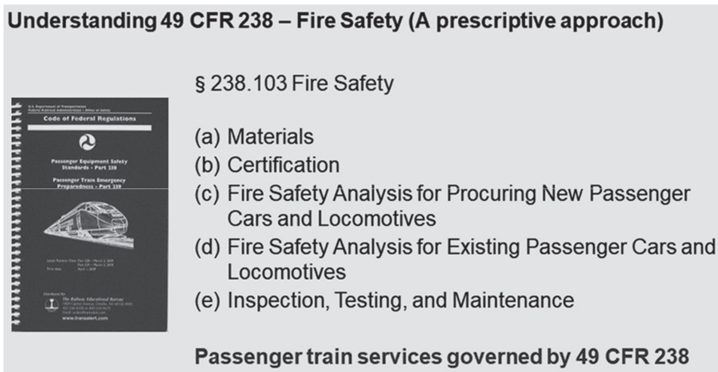


Figure 4.3.6. Fire Safety Standards, 49 CFR § 238 (1999–2019) (source: author's own work)

CFG management also reviewed the history of the federal regulations. Unlike in Europe, where there is a very robust regulatory and normalisation effort to continually improve fire standards (e.g. Fire Safety Standard EN 44545), passenger equipment safety standards in the USA have remained largely unchanged since 2002 (Figure 4.3.7).

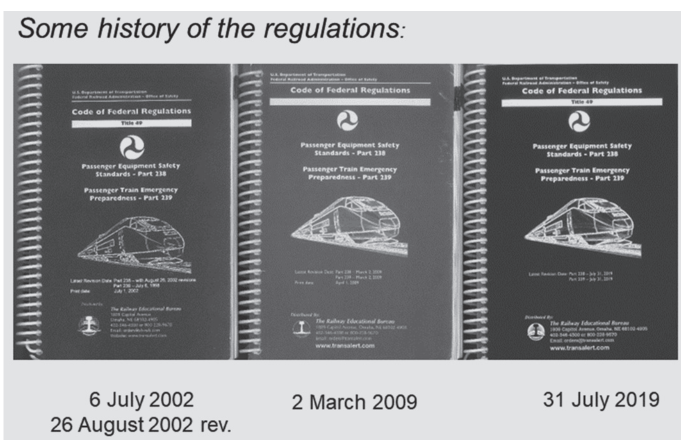


Figure 4.3.7. Revision History of Passenger Equipment Safety Standards 49 CFR § 238 (2002–2019) (source: author's own work)

As with any U.S. federal regulation, there is always a section on "applicability". What CFG found was that for its Executive Rail service, the federal regulation did not apply. As stated in the regulation, under § 238.3(c), "This part [of the regulation] does not apply to: (3) Tourist, scenic, historic, or excursion operations, whether on or off the general railroad system of transportation."

Thus, CFG could take guidance from, and be informed by, the federal regulation, but it was not legally governed by the regulation.

If the federal regulation had been applicable, Executive Rail would have been considered to be "the railroad" under the regulations and would have had ultimate responsibility for assuring that a reasonable level of fire and life safety is achieved for the safety of its employees, contractors and passengers.

4.3.3. The Passenger Rail Carriage *Catalpa Falls*

The *Catalpa Falls* (the *Catalpa*) was built by the Pullman Standard Car Manufacturing Company (Pullman) for the account of the Pennsylvania Railroad Company (PRR). The *Catalpa* was part of a 95-car order (Lot 6792) placed by the PRR with Pullman in August of 1946 and was one of eleven cars built to floor plan #4131. Delivered to the PRR in 1949, the *Catalpa* was among a larger group of cars assigned to a general pool of equipment for use on the railroad's first-class trains. Records indicate that the *Catalpa Falls* ran on the famous New York to Chicago *Broadway Limited*, the New York to St. Louis *Spirit of St. Louis*, and most other PRR streamliners, often referred to as *The Blue-Ribbon Fleet.*

The ownership of the *Catalpa Falls* transferred to the Penn Central Railroad after the merger of the Pennsylvania Railroad with the New York Central Railroad. The car was then sold by the Penn Central at auction in 1972 when it was transferred into the private ownership of George & Marcia Payne. In 2003, the Paynes partnered with Bob Andrews to form The Catalpa Falls Group, LLC of San Antonio, Texas, which now owns the *Catalpa Falls*. The *Catalpa* is currently based in Philadelphia, Pennsylvania.

As was indicated previously, the *Catalpa* was one of the 11 cars in the postwar PRR *Falls* series. The car still sports its original six double bedrooms, buffet (small kitchen) and lounge (Figure 4.3.8). Each bedroom is equipped with a lower and upper berth, as well as a separate enclosed lavatory that contains a toilet and fold-down sink. Each pair of bedrooms may be opened to form a larger suite. The lounge seats 20 and the car sleeps 12 on longer overnight trips representing a maximum occupancy of 32 passengers in day-service plus crew. Minor changes to the *Catalpa* which are shown in Figure 4.3.8 include the addition of a shower & relocated general toilet (which replaced the original Porter's station, the addition of a clothes washer & dryer (which replaced the original linen closet, an 18-inch expansion of the buffet into the lounge, the installation of a bar (which replaced the original magazine stand) and the addition of a crew workspace (which replaced the original general toilet).

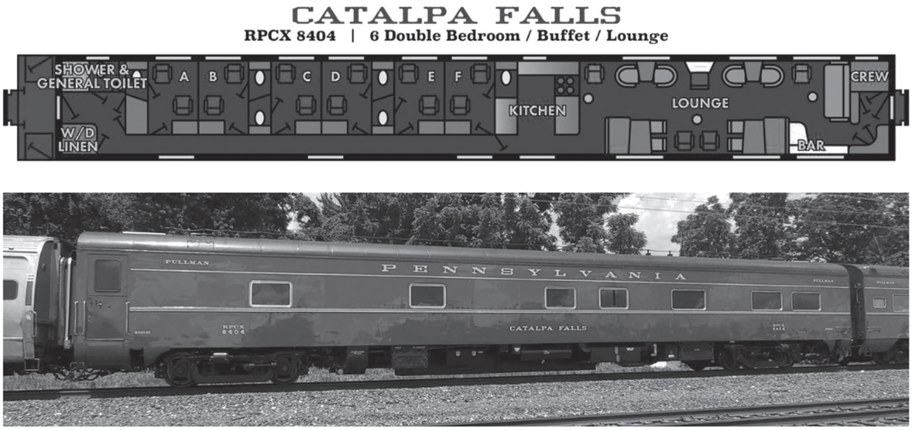


Figure 4.3.8. Current floor plan and exterior photo of the *Catalpa Falls* (source: property of author)

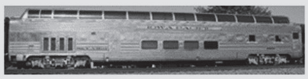
4.3.4. Economic and Supply Chain Factors Affecting New Passenger Carriages in the United States

To understand some of the pressures placed on Catalpa Falls Group management, one needs to compare and contrast the differences in the passenger rail market in the United States, with say, Europe. The use of passenger trains for intercity travel has steadily declined in the United States since the early 1960s. This has been due to the large size of the USA, the development of the U.S. interstate highway system, and the advent of the jet aeroplane. Due to these realities, inter-city long-distance passenger rail travel in the USA is a fraction of that in Europe, where there is a current renaissance of new overnight passenger rail being offered in numerous markets. Subsequently, there is a robust manufacturing capacity that has arisen to provide new, state-of-the-art, carriages to support this European renaissance.

In the United States, there is no such renaissance of overnight, long-distance, train travel. To accentuate this point, the last single-level sleeping carriages have just been delivered to Amtrak (America's long-distance train operator) and there are no new cars on order and the factory that built these latest cars is winding down its production line. The last order of bi-level sleeping cars was delivered to Amtrak in 1996 and any chance of a new order for bi-level sleeping cars is years away.

Subsequently, for Executive Rail's demand, there is no current source of new sleeper carriages available to meet its needs. Thus, ER must look to the "used" or "heritage" fleet and then, determine the best means of retrofitting fire and life safety provisions to these existing carriages. Adding to the difficulty is that without new sleeper carriages being in production, none of the "soft goods" (furniture and fixtures, carpet, fabrics and upholstery, curtains and blinds, etc.) that meet current smoke, flame, and toxicity standards (specifically aimed at the federal rail standard) are available. CFG/ER evaluated the theoretical business case comparison shown in Figure 4.3.9.

Unique opportunities and challenges related to "heritage" passenger carriages – Initial Comparison Opportunities

	"Heritage"	"New"
		
Built	1920 – 1965	Present Day
Current Acquisition Cost	$10,000 – $300,000	N/A (no recent orders placed)
Rebuild Cost	Varies	N/A
Total Investment	$500,000 – $1.5 Million	$2 – 3.5 Million*
Acquisition Time	1 – 1.5 Years	3 – 4 Years ++ (Approval – Design – Construction – Delivery)

Opportunity = Up to 75% lower cost and a minimum 2-year faster delivery ++

*The Superliner II fleet of 140 cars built in 1993-94 cost $340 Million ($2.42 million average per car).
++ The current Amtrak single-level car order from CAFS is approximately 10 years behind schedule.

Figure 4.3.9. A comparison of "heritage" vs. "new" passenger rail carriages in the USA (source: author's own work)

4.3.5. The Catalpa Falls Group's Fire Protection and Life Safety Philosophy

When it came to having to develop a fire protection and life safety philosophy, the Catalpa Falls Group was facing three conflicting priorities:

1. The need to use heritage carriages as part of our marketing "brand".
2. The extremely limited passenger rail carriage supply chain in the USA.
3. Economic considerations (as a for-profit company receiving no government subsidy).

In the end, the CFG management adopted the following philosophy:

> *As railroad operators, we live with the <u>constant</u> <u>tension</u> between achieving <u>ultimate theoretical safety</u> and meeting the <u>operating realities</u>* of running a for-profit business that receives no government subsidy. Thus, our goal is to implement the *<u>art-of-the-possible</u>, as best we can.*

A graphic depiction of this constant tension is shown in Figure 4.3.10 (https://images.app.goo.gl/TxgdTkcEvGBcmax39).

Figure 4.3.10. Depiction of the "tug of war" between "ultimate theoretical safety" and "operating realities"

4.3.6. Fire Protection and Life Safety Features Incorporated in the Rebuilding of the *Catalpa Falls* — The Case Study

Appendix B to Part 238 [of the U.S. federal regulation] — *Test Methods and Performance Criteria for the Flammability and Smoke Emission Characteristics of Materials Used in Passenger Cars and Locomotive Cabs* provides specific guidance regarding the use of materials used in passenger cars. It became immediately clear to CFG management that complying with the specific requirements contained in Appendix B was not practical from both a technical and a financial perspective. Subsequently, CFG management and the company's Chief Engineer set out to identify countermeasures that could be applied to improve the fire and life safety of the *Catalpa Falls* from its original, as-built condition. The overall goal of CFG management was to provide a *reasonable level of fire and life safety.* To help evaluate hazards that existed on the *Catalpa Falls* in its original condition, a Fire Safety Analysis was performed (see Figure 4.3.11 for details).

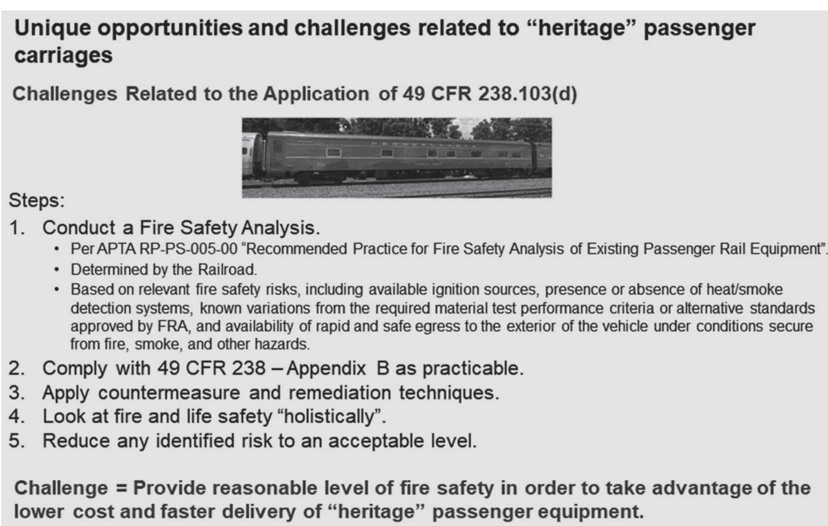


Figure 4.3.11. Steps to applying the Fire Safety Analysis for the *Catalpa Falls* (source: author's own work)

At the conclusion of the fire safety analysis, four major areas for improvement of the physical carriage were identified:

1. The installation of a comprehensive fire detection and alarm system.
2. The installation of an emergency public address and passenger notification system.
3. The provision of fire- and smoke-tested interior fabrics.
4. The addition of emergency exit windows.

Further explanation of these improvements is included in Figures 4.3.12–4.3.14.

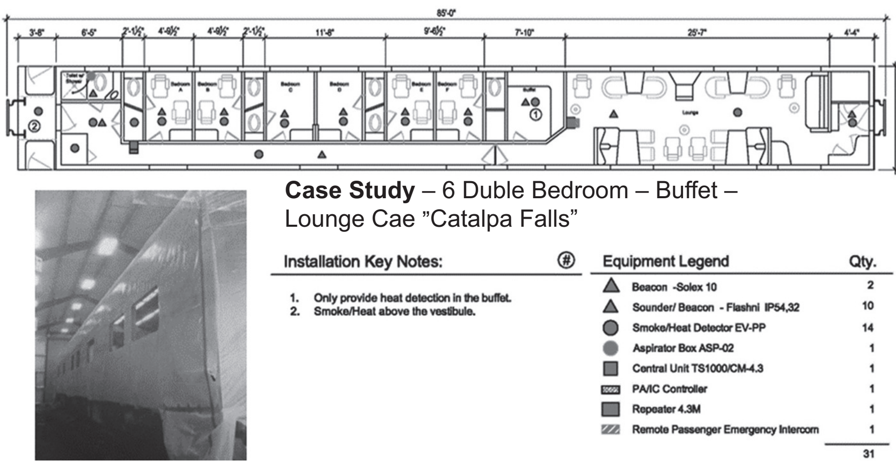


Figure 4.3.12. Floor plan of the *Catalpa Falls* showing the types and locations of new fire protection and life safety equipment (source: author's own work)

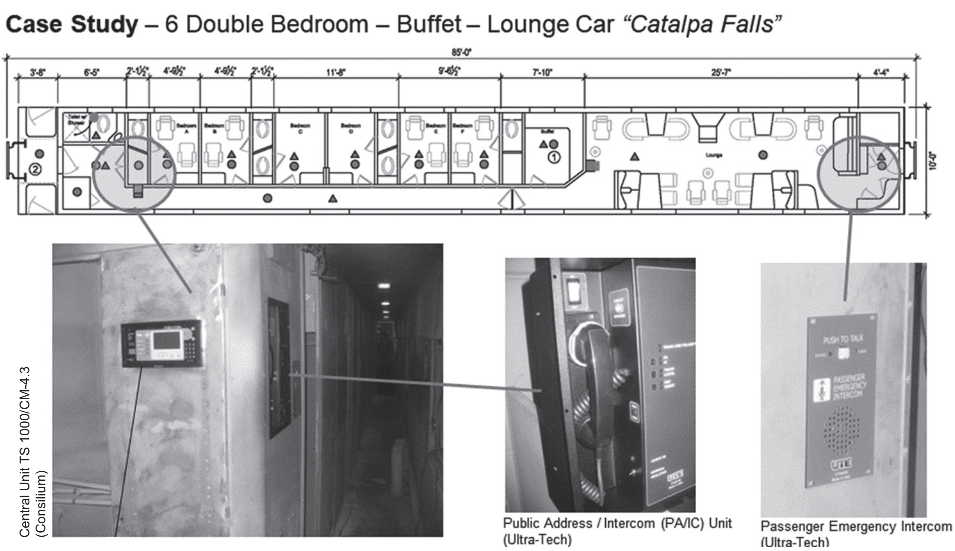


Figure 4.3.13. Main fire alarm panel, public address intercom and passenger emergency alarm (source: author's own work)

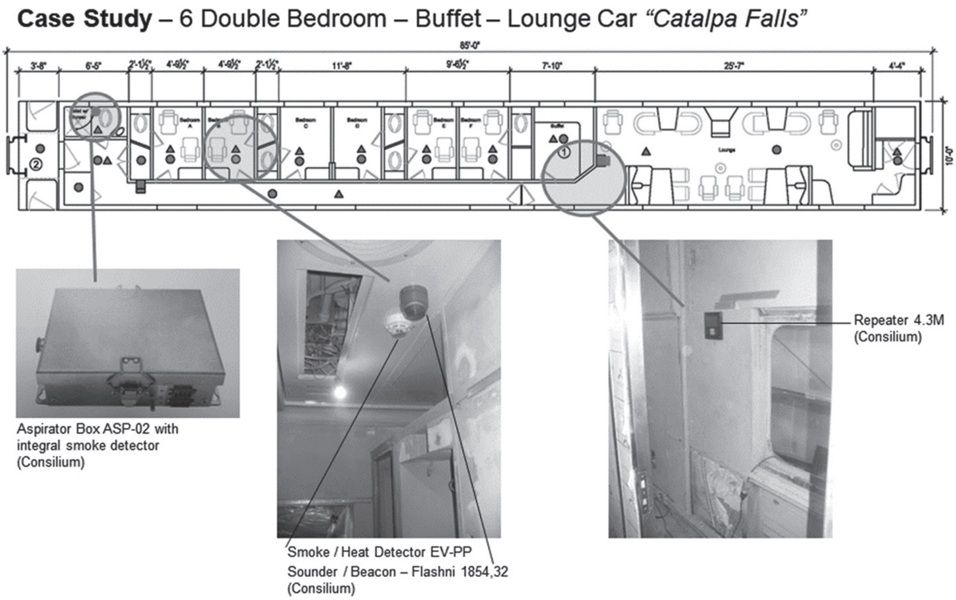


Figure 4.3.14. Interior view of aspirator box above the shower/general toilet, a smoke detector and sounder/beacon in a bedroom, and the annunciator (fire alarm) repeater outside of the buffet (source: author’s own work)

A significant component of the fire and life safety improvements on the *Catalpa* Falls involved the provision of fire- and smoke-tested interior fabrics. As was mentioned in the previous section, the current passenger carriage supply chain in the United States does not produce materials that are compliant under Appendix B to Part 238, except for pull-down type roller shades.

To best accommodate the spirit of Appendix B, CFG management sourced materials that were aircraft-compliant (Boeing or Airbus approved). CFG’s rationale was that if the materials were acceptable for twin-engine aircraft that could be airborne and 60 minutes from landing under EDTO — *Extended Diversion Time Operations* (formerly ETOPS — extended-range twin-engine operational performance standards), then the fabrics should be acceptable for passenger rail operations where evacuation times from the passenger carriage were much shorter.

Materials used in carpet, fabrics for furniture, mattresses and curtains were all approved for commercial airliner use by Boeing and Airbus and met both U.S. and European aircraft safety standards. Photographs of the *Catalpa Falls* lounge are shown in Figure 4.3.15.

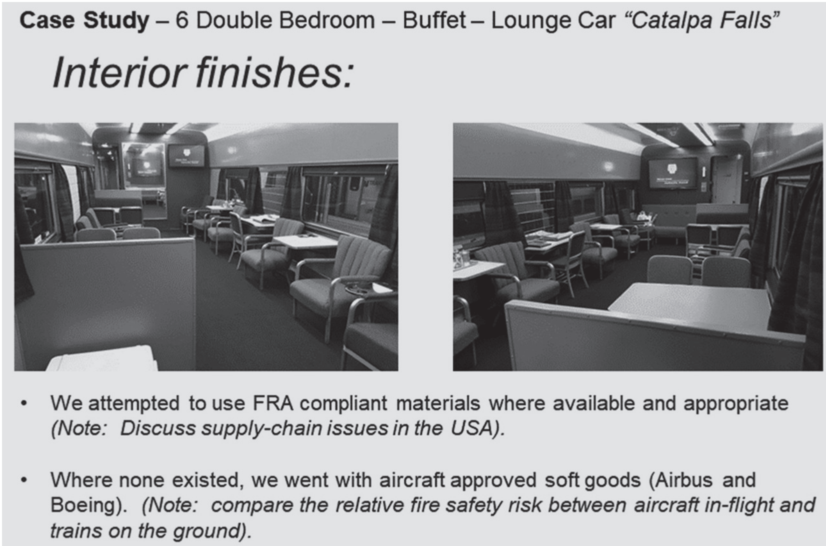


Figure 4.3.15. Interior view of the *Catalpa Falls* 20-person lounge (source: author's own work)

4.3.7. Promising Future Technology for Heritage Carriages in the Executive Rail Fleet

Some fire protection and life safety technology was evaluated by CFG management but not incorporated into the *Catalpa Falls* refurbishment programme. Specifically, the use of phenolic flooring and water-mist systems, while very interesting, was not deemed to be practicable at the time of the refurbishment.

Phenolic flooring, such as that manufactured by Milwaukee Composites, Incorporated (MCI) has excellent fire resistance qualities and can pass the stringent ASTM E-119 Fire Endurance Test. Additionally, MCI has developed a heater element that can be moulded into the top skin of their standard floor panel to provide a robust system that can eliminate the need for sidewall heaters. CFG management believes this flooring system could be very beneficial to the CFG fleet in certain circumstances where the floor plan of the carriage lends itself to total replacement (such as in a coach). In the case of the *Catalpa Falls*, due to the numerous wall partitions, replacement of the existing floor was not deemed to be practicable.

CFG management is also very interested in the application of water-mist technology in its fleet. However, at the time of the refurbishment of the *Catalpa Falls*, a single-car water-mist system was not available and the cost of custom-engineering a single-car system was prohibitive. At the time of refurbishment, water-mist systems were being designed for multi-car train sets and the engineering cost was being spread amongst several train sets. CFG is continuing to look for an affordable single-car water mist system/technology.

The use of cell phones, smart pads, and laptop devices for the receipt of alarms and status reports from rail carriages continues to improve. Recently, CFG identified and installed a GPS/cell phone-based monitoring and alerting system in its fleet. The system currently monitors the location of the carriage, temperature (inside and outside the carriage), intruder entry, excessive g-forces (due to hard coupling), and the status of 480-volt electrical shore power. Integration of this telemetry system with the fleet's fire alarm and detection system is under way.

A graphic depiction of these technologies can be found in Figure 4.3.16.

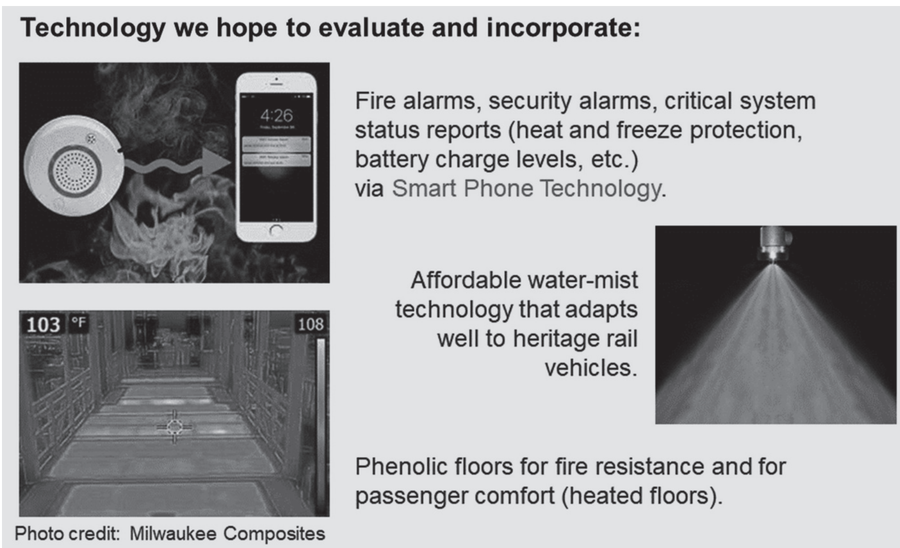


Figure 4.3.16. Technology to be considered for future Catalpa Falls Group rail carriages (source: author's own work)

4.3.8. Conclusion

Improvements in the fire and life safety of heritage passenger rail carriages can be achieved through the practice of fire protection engineering and the application of significant engineering judgement and design creativity. Countermeasures (also referred to as "alternatives", "remedial actions", "equivalents", etc.) can be applied that help mitigate fire and life safety shortcomings due to the age of the passenger rail carriage and its original date of manufacture. This case study evaluated a single railroad carriage, the *Catalpa Falls*, which was originally delivered in 1949, and is now 73 years old. The countermeasures employed reflect advances in technology, human factors and emergency procedures, which were not currently known or available at the time of the car's original design and construction. Countermeasures employed in the major renovation of the *Catalpa Falls* included fire detection and alarm systems; smoke and flammability tested carpet, fabrics for furniture, mattresses, curtains and window shades; a public address and passenger emergency intercom system; additional emergency exit windows; photoluminescent emergency signs; crew emergency preparedness training; enhanced passenger safety information; and a remote carriage monitoring system utilising cellular phone and GPS technology. Future countermeasure technologies that were identified, but were not incorporated into the *Catalpa Falls,* included the use of phenolic flooring to improve the fire resistance of the carriage floor assembly (incorporating integrated heating elements to improve passenger comfort), as well as a water-mist fire suppression system.

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[1] Passenger Equipment Safety Standards, 49 CFR § 238 (1999–2019), https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II/part-238.

[2] Passenger Train Emergency Preparedness, 49 CFR § 239 (1998–2019), https://www.ecfr.gov/current/title-49/subtitle-B/chapter-II/part-239.

5 Alternative Power in Rolling Stock

The interest in alternative fuels results from the depletion of crude oil resources and, consequently, from the search for new energy sources. Since the late 1960s, the discovery of new deposits and the volume of extraction have been systematically decreasing despite the use of increasingly modern technological solutions, including satellite research. The great difficulty of access to the discovered deposits, the higher density of oil and, for example, its saturation with toxic hydrogen sulphide, require more complicated and expensive exploitation and processing techniques, as well as special precautions. According to available data [2, 4], it is estimated that currently oil consumption exceeds newly discovered oil reserves and these, in any case, are estimated to last less than 100 years.

Considering the declining crude oil reserves, as well as the increased awareness of the negative environmental impacts caused by gases and solid particles emitted during the combustion of hydrocarbon fuels, the search for alternative fuels was undertaken. Within the meaning of the directive [3], these include fuels that are used, at least partially, as a substitute for energy sources derived from crude oil, and which have the potential to reduce the dependence of EU Member States on oil imports. The search in question concerns applications in various areas of the economy, including transport.

Another important argument is the desire to decarbonise transport and improve the environmental performance of this sector. Alternative fuels include electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas (including biomethane) in the form of Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG).

Exploration activities are supported by legislative acts, including the European Green Deal [4] approved on 13 December 2019 by the European Commission, which has adopted, among other things, the goal of reducing greenhouse gas emissions in the transport industry by 95% by 2050.

Increasing the use of alternative power supply in railway vehicles has recently been the subject of many discussions and conferences, but there are still few publications in this area (for example, the paper presented at the XXV Scientific Conference Rail Vehicles 2023 [4]). Due to its importance and the need to undertake research and legislative activities, this issue, which was also the subject of the conference mentioned in the introduction (5th International Conference "Modern Directions in Fire Protection of Rolling Stock", organised by the Railway Research Institute), could not be omitted in this monograph. This chapter updates and expands the article [1].

It discusses alternative power sources for rail vehicles, presenting their advantages and disadvantages and particularly characterising the cases of uncontrolled ignition. Further, it draws attention to the need to develop European regulations regarding the fire safety of rail vehicles using hydrogen cells, lithium batteries and natural gas. Such requirements are particularly important for rolling stock passing through tunnels and should also cover vehicles with alternative drives as well as those transporting cargo like discharged lithium batteries, electric bicycles or scooters.

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[2] Siwiec J., Zastosowanie wodorowych ogniw paliwowych w transporcie kolejowym, DOI: 10.36137/1906P, Problemy Kolejnictwa, ISSN 0552-2145 (print), Issue 190, 2021, Vol. 65/2021, pp. 53–57, ISSN 2544-9451 (online).

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[3] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, The European Green Deal, Brussels, 11.12.2019 COM(2019) 640 final.

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[4] https://ziemianarozdrozu.pl/encyklopedia/74/kiedy-zabraknie-ropy.

[5] https://konferencje-k53.pwr.edu.pl/event/1/contributions/22/ (information on the paper: Kowalski P., Wodór jako alternatywne źródło energii w pojazdach kolejowych).

5.1. Fire Hazard in Rail Vehicles with Alternative Power Sources

The global trend of implementing alternative fuels has also extended to rail transport, which is expected to use primarily the following power sources:

- electric batteries (supplied with a charging station),
- natural gas (supplied with a refuelling station),
- hydrogen (supplied with a refuelling station),
- hybrid power supply.

Their characteristics and current examples of use are presented below.

5.1.1. Lithium Batteries

In 2019, John Goodenough, Stanley Whittingham and Akira Yoshino, three scientists whose research began in the 1970s, received the Nobel Prise in Chemistry for the development of lithium-ion batteries. The forerunner of lithium battery experiments was the American chemical physicist George Newton Lewis, who commenced them as early as 1912. The first lithium-based battery was marketed in 1978 by Exxon. However, they only became widespread after Sony launched a series of lithium-ion batteries in 1991 [32, 33]. Figure 5.1.1 shows a diagram of a lithium-ion battery.

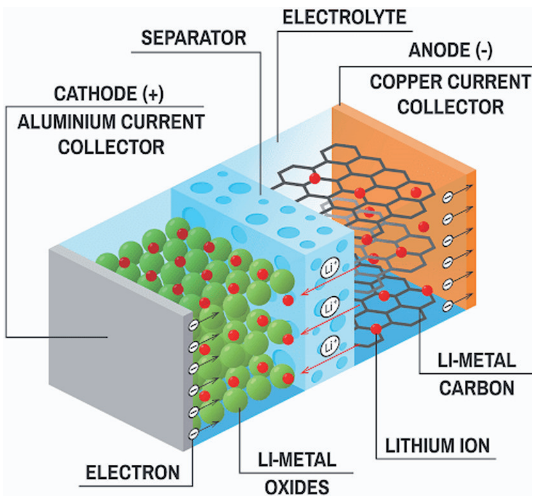

Figure 5.1.1. Diagram of a Li-Ion battery [47]

The battery consists of a positively charged cathode made of graphite and a negatively charged anode made of lithium. The other two parts contain the electrolyte and the separator between the two charged electrodes. During charging, lithium ions move from a carbon anode to a cathode made of lithium oxide and another metal and are stored there.

The advantages of lithium batteries compared to other types of batteries (e.g. NiCd and NiMH) include:

- 3 times more capacity with the same battery size,
- lower weight,
- many times higher energy density,
- no memory effect,
- no heavy metals (environmentally friendly),
- wide operating temperature range (from as low as –20°C to as high as 50°C),

- longer service life,
- the most developed nanocrystalline structure of the anode in the case of lithium titanate $Li_4Ti_5O_{12}$ (LTO) batteries (high surface stability; the charge is transferred much faster and the permissible currents are higher).

Li-Ion batteries also have drawbacks. These include fires and explosions that occur when the anode and cathode short out due to:
- spilled fuel fire,
- overheating due to incorrect charging or overcharging,
- battery design errors.

The result is a rapidly progressing and often uncontrollable chain reaction. The temperature increases rapidly and the separator between the electrodes melts. This causes further heating of the battery and a loss of control over the increase in system temperature, which leads to the thermal runaway effect (Figure 5.1.2). By this point, we are dealing with a chain reaction, which is especially dangerous in multi-cell batteries, as it triggers a reaction in other, often undamaged, cells. As the temperature increases, the cathode begins releasing oxygen, which reacts with the organic electrolyte, ultimately causing the battery to ignite or explode (Figure 5.1.6).

Some high-profile cases in this regard include explosions of phone batteries aboard aeroplanes (Figure 5.1.3), an explosion of an electric bicycle battery (Figure 5.1.5), as well as a battery explosion in a Tesla car (resulting in the driver's death) (Figure 5.1.4). Indeed, the wreck of that car, which by that point had been towed to a car park, spontaneously exploded and caught fire again six days after the accident [28, 30].

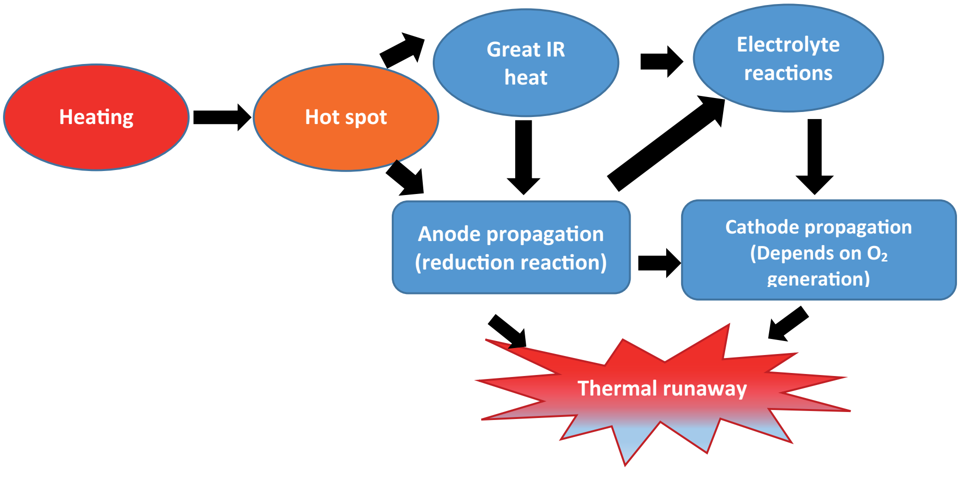

Figure 5.1.2. Thermal runaway mechanism of a lithium-ion battery under heating conditions [3]

The largest fire in rail transport occurred on 23 April 2017, on a Union Pacific train, when a container carrying discharged lithium batteries intended for recycling caught fire [31].

Figure 5.1.3. Explosions of lithium batteries in mobile phones [48]

Figure 5.1.4. Lithium battery fire in a Tesla car [49]

Figure 5.1.5. Lithium battery fire in a motorcycle [50]

Figure 5.1.6. Lithium battery fire on a Union Pacific train [31]

Lithium Batteries in Rail Vehicle Power Systems

In rail vehicles, lithium batteries are used as the main energy source and as energy storage in the case of hydrogen-powered units.

Ultra-high-power on-board lithium battery systems for railway applications are a reliable on-board power source for catenary-free operations and play a key role in the greening of the railway landscape.

5.1.2. Hydrogen — Properties and Applications

The prospect of using hydrogen as a fuel in transport has enormous potential for the following reasons:

- it is virtually unlimited (it constitutes 94% of the universe),
- it is considered the cleanest fuel from an ecological standpoint (the product of hydrogen combustion is water vapour),

- it easily creates a homogeneous flammable mixture (a high diffusion coefficient of H_2 in air),
- it is the lightest fuel in any state of matter,
- it has the highest calorific value of fuel per mass (120 MJ/kg),
- is a very reactive fuel, characterised by a high octane number and combustion speed.

Because of these reasons, it is considered the fuel of the future. However, this fuel also has some disadvantages:

- it is a colourless and odourless gas that is extremely flammable and very explosive in mixtures with air,
- hydrogen flame burning in the air at atmospheric pressure is invisible (which is particularly dangerous),
- it causes hydrogen corrosion of metals, decarburisation of steel, brittleness of welds and destruction of plastics,
- leakage from the tank may cause combustion deflagration and even detonation in a tunnel [2].

Moreover, one significant disadvantage of hydrogen cells is their high production cost.

The operating diagram of a hydrogen cell was developed as early as 1838 by the German-Swiss chemist Christian Friedrich Schönbein. However, the breakthrough in their use came only in the 1960s, when they were used aboard a NASA spacecraft. Figure 5.1.7 shows the operating diagram of a hydrogen cell.

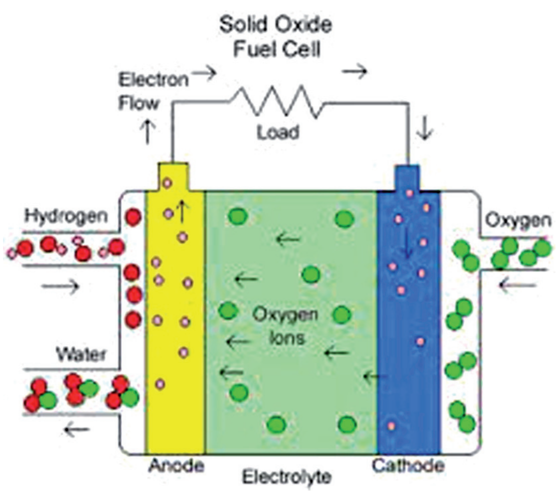

Figure 5.1.7. Diagram of a hydrogen cell [41]

The cell consists of two electrodes — a cathode and an anode — separated by an electrolyte or an electrolytic membrane. Typically, the electrodes take the form of carburised paper coated with platinum as a reaction catalyst. After hydrogen is supplied to the cell, it oxidises (releases electrons), resulting in the formation of hydrogen cations. At the cathode, oxygen reacts with electrons, becoming reduced to oxygen anions. The membrane inside allows protons to flow from the anode to the cathode while blocking other ions, including the formed oxygen anions. After reaching the cathode, hydrogen cations react with oxide anions to produce water and electrons from the anode reach the cathode through an electrical circuit, producing energy.

Hydrogen-Powered Rail Vehicles

The first fuel cell train was the Coradia iLint multiple unit (Figure 5.1.8), manufactured by the Swiss company Alstom in Salzgitter and introduced into public transport service on 17 September 2018. This vehicle covers a route of approximately 100 km from Cuxhaven to Buxtehude in Lower Saxony (Germany). At the same time, it should be noted that apart from a set of fuel cells, its drive system also includes a lithium-ion battery system, an external converter, a hydrogen tank, a traction inverter and a traction motor [1].

Figure 5.1.8. Coradia iLint multiple unit [43]

The Polish company PESA, based in Bydgoszcz, also produced a hydrogen locomotive — the SM42Dn (Figure 5.1.9). It uses 4 asynchronous electric motors with a total power of 720 kW, an LTO (lithium titanate) battery with a capacity of 167.7 kWh and ABB traction inverters with a 3 × 400 V auxiliary converter. Its hydrogen fuel is stored in tanks pressurised to 350 bar. The power sources are two Canadian-made Ballard fuel cells with a total power of 170 kW [28].

Figure 5.1.9. PESA SM42Dn hydrogen-powered locomotive [44]

January 2021 saw the launch of the European FCH2RAIL project (Figure 5.1.10) with partners from Belgium, Germany, Spain and Portugal. Their task is to develop a new zero-emission train prototype. The vehicle is to be equipped with a hybrid and modular drive system, combining electricity from the overhead line with fuel cell power. The latter will involve using fuel cells and batteries. They must be connected and controlled so that the system meets all the relevant requirements and is profitable.

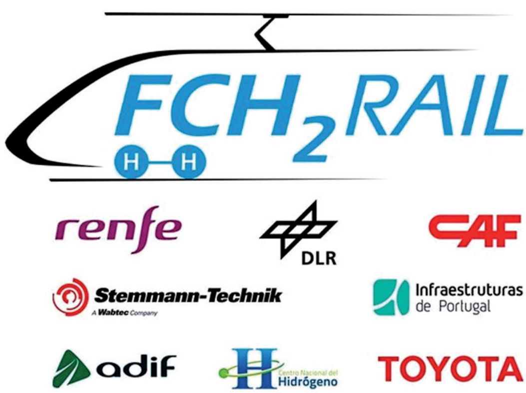

Figure 5.1.10. Logo of the FCH2RAIL project [45]

Another EU-funded SherLOHCk project titled “Sustainable and Cost-Efficient Catalyst for Hydrogen and Energy Storage Applications Based on Liquid Organic Hydrogen Carriers: Economic Viability for Market Uptake” [46] aims to solve the key problem of hydrogen storage.

One solution could be liquid organic hydrogen carriers capable of storing large amounts of hydrogen and releasing pure hydrogen on demand. The project will develop active and selective catalysts with partial or complete replacement of the platinum group metals. Project partners will also develop innovative catalytic system architecture to reduce the energy consumption of the charging and discharging processes. To minimise internal heat losses and increase space and time efficiency, this architecture will include both a catalytic converter and a heat exchanger.

5.1.3. Blue Fuel, i.e. Natural Gas

Natural gas is also called the fuel of the 21st century. While its composition may change based on the location of the deposit from which it is sourced, its main component is always methane.

Natural gas has no odour, so it is specially odourised to make it easier to smell in the event of a leak.

This fuel has several advantages over other propulsion methods, including:

- high caloric value,
- low exhaust emissions — 10% lower CO_2 emissions and 100% lower particulate matter (soot) emissions.

In rail vehicles, it is used in compressed (CNG) or liquefied (LNG) form. Examples of natural gas-powered vehicles are shown in Figures 5.1.11–5.1.14.

Figure 5.1.11. Freight locomotive on the Jacksonville-Miami route (Florida, USA) [35]

Figure 5.1.12. Renfe train (Spain) under the EU-funded RaiLNG programme [37]

Figure 5.1.13. Railbus for transporting tourists around Rimini (Italy) [37]

Figure 5.1.14. Railbus in the Czech Giant Mountains on the Martinice v Krkonoších railway line from Rokytnice nad Jizerou, 2022 [36]

5.1.4. Fire Safety of Rail Vehicles With Alternative Drives

Rail vehicles running on the interoperable TEN network must meet the requirements of the following technical specifications for interoperability:
- passenger rolling stock: LOC&PAS TSI [11],
- freight rolling stock: WAG TSI [10],
- and in the case of rolling stock running through tunnels, also: SRT TSI [12].

Regarding fire safety, these specifications refer to the EN 45545 series of standards (Parts 1 to 7) [20] in individual areas to ensure the safety of passengers and train crew by minimising the impact of the products of a possible fire. Part 7 specifies requirements for flammable liquid and liquefied hydrocarbon gas installations. It also refers to the requirements of EN 50153 [21] for containers and pipes, EN 10204 [18] for any metal used in flammable liquid or gas installations and EN 15227 [19] for LPG cylinders. Nonetheless, this series of standards does not cover the implementation of alternative drives and does not contain special requirements dedicated to them. This is because such installations began to be implemented in rail transport after the establishment of EN 45545 [20].

As noted in Chapter 1.1 of this monograph, guidelines for the application of EN 45545-2 for Ni-Cd batteries in railway rolling stock have been developed only for Ni-Cd batteries (WG CLC/TC 9X Technical Report CLC/TR 50718:2021) [25]. They recommend treating the battery as an unspecified product in accordance with EN 45545-2 [20] and the option to apply section 4.7 regarding the approval due to functional necessity until the work of the SG31 Group is completed.

However, battery systems containing lithium-ion cells still pose a challenge in terms of fire safety. Extinguishing such fires remains a problem for rescue services. Research conducted by the Federal Aviation Administration (FAA) in the USA showed that water-based fire extinguishing materials were the most effective. Effective measures relied on a combination of extinguishing the burning electrolyte and simultaneous cooling of the cell. In contrast, gas-based extinguishing agents showed good ability to extinguish the burning electrolyte but were unable to adequately cool the cell. That is why there is a risk of another spontaneous fire, even many hours after the initial one is extinguished (as in the case of the Tesla accident mentioned at the beginning).

Considering the above, the upcoming 2024–2026 revision of EN 45545-5 [20] will also see the WG01 group address the requirements for hydrogen batteries, traction batteries and new supply technologies.

It is necessary to adapt the current requirements for the installation elements of alternative drives, taking into account the characteristic properties of individual systems. This includes requirements for hydrogen installations to prevent uncontrolled leaks. Requirements for alternatively-powered vehicles should also consider the impact of a possible hazardous event such as derailment, collision or spread of fire in another area of the train.

It is considered advisable to adapt the requirements intended for hydrogen-powered road vehicles, including Regulation (EU) 2019/1243 [16] and Regulation No. 134 (UN/ECE) [15]. However, due to the use of hybrid drives in rail vehicles, approval procedures should also include tests and requirements for lithium batteries.

The previously described cases of spontaneous combustion and explosion of lithium batteries resulted in research aimed at identifying the fire hazards they pose. The research involved batteries of various sizes with different degrees of charge and multiple methodologies and research stations (furniture calorimeter [3], Tewarson apparatus, CDG calorimeter [5], adapted decompression chamber [7], Single Burning Item (SBI) apparatus [4], as well as the rechargeable energy storage system (REESS) procedure according to R100.02 [14].

All tests performed constitute an important contribution to identifying phenomena occurring in uncontrolled situations and involving lithium batteries. Among other things, they confirmed that the more charged the battery is, the faster the ignition occurs from the initiated source, as well as that the Heat Release Rate value increases with the battery charge level [4]. The results of the above tests also showed the release of toxic combustion products like sulphur dioxide or hydrogen fluoride (depending on the composition of the battery's electrolyte) which, if ignited in a closed/confined space, e.g. in a passenger train passing through a tunnel, may constitute a significant danger to people. However, selecting approval tests requires detailed clarification to ensure method repeatability [27].

European requirements for fire safety of rail vehicles also do not cover the specificity of natural gas supply. However, documents like ISO 12991:2012 [22], NFPA 52 [23] and NFPA 59A [24], regarding the production, storage and use of LNG in motor vehicles, may be helpful in this respect.

5.1.5. Conclusions

Declining fossil fuel reserves forced the search for other energy sources, including for powering rail vehicles. Applying increasingly innovative technologies results in greater use of alternative fuels. Replacing petroleum-based fuels with new types of power has a positive impact on the environment. Nonetheless, it requires the development of European regulations regarding the fire safety of rail vehicles using alternative fuels such as hydrogen cells, lithium batteries and natural gas. While this applies primarily to passenger rolling stock running through tunnels, such regulations should also cover freight rolling stock carrying cargo like electric scooters, bicycles and motorcycles.

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