

RESEARCH ARTICLE

Fire safety of interior materials of buses

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Abstract

This study provides an analysis on the fire safety of passengers and the fire protection of coaches and buses. A brief review of major bus fire incidents, an overview of current regulations in Europe, and their limitations are presented. The study finds that the current small-scale fire test methods described in UN ECE Reg No. 118 need to be replaced by test methods that can assess the reaction to fire of materials when exposed to ignition sources of varying sizes. To address these shortcomings, the study proposed an expert recommendation to update the material fire safety requirements and testing for buses. Additional measures are proposed, derived from objectives and strategies applied in other transport sectors, and can be tested through existing European and international standards, which are widely used by several industries. These measures aim to extend the time with tenable conditions for a safe evacuation in case of fire, reduce the degree of damage to buses, reduce the risk for fast and excessive thermal exposure on modern energy carriers needed for a more sustainable transport sector.

KEYWORDS

bus, coach, fire safety, interior materials, regulation, testing methods

1 | INTRODUCTION

In recent years, the use of collective means of transport, such as buses, has been encouraged to reduce pollution and congestion in cities. In addition, long-distance bus travel has become more popular due to its cost-effectiveness compared to other forms of transportation. However, fire safety regulations for buses are not as stringent as those for other modes of transport. As buses are increasingly being used for long-distance travel and overnight trips, more stringent fire safety regulations are necessary to ensure safe evacuation of passengers in the event of a fire. Factors such as the aging population in European countries and the potential for a high number of sleeping

passengers can make evacuation more difficult. In addition, bus fires that occur as a result of collisions can result in passengers being unconscious or injured, making evacuation more challenging. The rise of new transportation technologies, such as electric and hydrogen-powered buses, also highlights the need to re-evaluate current fire safety tests and standards for these vehicles. This study provides an opinion on fire safety of passengers and the fire protection of coaches and buses and aims to address the shortcomings of current fire safety regulations and propose additional measures for the protection of passengers and buses. We will provide a review of major bus fire incidents and an overview of current regulations in Europe, as well as identify shortcomings in materials used in bus interiors. Finally, we will

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propose measures derived from strategies used in other transport sectors to improve fire safety for buses. These measures can be translated into several fire requirements to be tested through existing European and international standards, which are widely used by several industries.

2 | MAJOR REAL-SCALE BUS FIRE TESTS

Bus fires are becoming more frequent, and while they remain relatively rare, their consequences can be severe, both on the human and financial aspects. A review of major bus fire tests and real fires involving buses is addressed. Data for large-scale bus fire tests is limited, let alone considering different fire scenarios and ignition sources.

Previously, numerous tests were performed on the interior bus products, that showed how to provide sufficient fire safety.^{1–5} However, only a limited number of real scale tests of entire buses or coaches have been performed. For example, Hammarström et al.⁶ conducted a large-scale fire test of a conventional coach for 49 passengers. The purpose of the test was to study fire development from the engine compartment into the passenger compartment and to assess smoke spread, visibility conditions, and concentrations of toxic gases in the passenger compartment. Finally, the heat release rate from the developed fire in the coach was also measured. The test showed that the available time for evacuation of the passengers was less than 5 min. After this time, the concentration of toxic gases reached dangerous levels. The experimental campaign also separately tested different components of the bus. These experimental results are corroborated by the fire rescue service in Gothenburg, Sweden, who reports that buses used for public transport show a high fire risk since the fire develops quickly. It takes just a few minutes to completely fill the bus with smoke, resulting in a very short evacuation time.⁷ The test results by Hammarström et al.⁶ were compared with existing criteria for other applications and the main conclusion was that the fire safety levels in the passenger compartment of buses were much lower than in other applications and that they are not sufficient.

Another full-scale fire experiment was conducted at the National Institute of Standards and Technology (NIST), to investigate the mode of penetration of a tire fire into the passenger compartment⁸ and the evolution of the tenability conditions.⁹ The bus interior was partially furnished with only three sets of seats. Measurements of interior and exterior temperatures, interior heat flux, heat release rate, toxic gases, and visibility were performed. In addition, standard and infrared videos were recorded. The experiments showed that the tire fires ignited the plastic fender and glass-reinforced plastic (GRP) exterior side panel (below the windows), upon which the fires spread quickly and penetrated the passenger compartment by breaking the windows. Measurements showed that other potential fire penetration routes (flooring and lavatory) lagged far behind the windows in heating and degradation. Fire-hardening using steel components had the greatest effect, followed by using an intumescent coating. The combination of three pairs of seats and partial trim installation was sufficient fuel

loading to compromise tenability conditions within 7 min near the fire and to reach well-developed fire in the rear half of the passenger compartment in less than 11 min after fire penetration. Visibility conditions (evaluated 1.5 m from the floor) deteriorated significantly prior to fire penetration of the motor coach. Within 30 s after penetration, visibility decreased to less than 2 m. Poor visibility could have made egress from this motor coach difficult several minutes before conditions became untenable. Untenable conditions for this experiment were attained with a limited fuel loading, suggesting that the conditions and timing observed in this experiment were not the most conservative.

3 | BUS FIRE ACCIDENTS

3.1 | Statistics

There are currently few detailed statistics regarding the number of fire incidents and the number of fire deaths occurring in buses. One of the challenges is to know the real number of accidents and fires occurring in buses. The number of unreported minor accidents and vehicle fires with limited consequences remains unknown. Even if they remain relatively rare, their consequences are impressive and severe, both on the financial and human aspects, and therefore make the statistical approach limited. Thus, it is yet quite impossible to provide generic statistical analysis of such accidents, as well as the number of victims, deceased or significantly hurt, without a full research project dedicated to this topic that could provide an accurate evaluation of the potential cost–benefit ratio of stronger fire safety regulation. Some data are provided in the literature.^{4,10–20}

Statistics in the USA have shown that in 2017 almost 168 000 highway vehicles (e.g., automobiles, buses, trucks, etc.) caught fire in the USA, which caused the death of 400 civilians, injured 1370, and led to \$1.4 billion in direct property damage.¹¹ An average of 1550 bus fires per year (1%) cause an average of 11 injuries (1%) and \$28 million in direct property damage (2%) annually.¹² The United States' National Transportation Safety Board revealed that as many as 2600 fires break out every year on buses in the USA alone, and that a great many more bus fires go unreported. Approximately six school bus fires are reported every day.¹²

Alonso and Rein reports²¹ that according to UK statistics a bus has 2.3 times higher probability for catching fire than a car, and approximately equal probability as heavy goods vehicles.^{22,23} Compared with other modes of transport, the probability for bus fires is 2.7 times higher than ships and 8 times higher than trains.²⁴ The Scottish Fire and Rescue Service statistics revealed that in nearly one in five of the fires, 40 of the total 213, the entire vehicle suffered fire or heat damage. Overall, the UK fire statistics show that for the last 10 years about 11 900 fires per year in vehicles are recorded, particularly 315 fires per year in buses.⁶ Studies show that fire incidents annually occur in 0.5%–1% of all registered buses/coaches.^{4,6,19} Dülse and Hofmann confirmed a review of fire events in a German bus association that observed that approximately

TABLE 1 Examples of bus fires.

Country, Location, Date	Fire source	Consequences
Bulgaria, Sofia, November 23, 2021	Bus rammed a crash barrier on a motorway	46 dead including 12 children, 7 escaped but hurt ²⁷
Germany, Stuttgart, October 11, 2021	Fire spread in bus depot. Possibly due to charging of electric bus.	No fatalities 25 buses ²⁸
Germany, Hanover, June 11, 2021	Fire spread in bus depot	No fatalities 9 buses ^{19,28}
Sweden, Skellefteå, March 16, 2020	Fire spread in bus depot	No fatalities 7 buses ²⁹
Germany, Bavaria, July 3, 2017	Coach collided with lorry	18 dead ^{30,31}
France, Puisseguin, October 23, 2015	Collision with semi-trailer truck. Coach's fuel tank bursted	43 dead ³²
Germany, Bottrop, December 25, 2011	Technical defect in one bus caused fire spread to 68 more buses in bus depot	No fatalities 69 buses Building 22 MEuro ³³
Germany, Hannover, November 24, 2008	Fire in bathroom with subsequent explosive fire spread in passenger compartment	20 dead ^{28,34}
Italy, Rome, September 8, 2009	Fire spread in bus depot	No fatalities 24 buses ³⁵
Poland, Bialystok, September 30, 2005	Collision with truck	11 dead and several dozens injured ³⁶
USA, Wilmer, Texas, September 23, 2005	Fire in wheelhouse	23 dead ¹⁰

0.5%–1% of the buses had a fire event per year.¹⁹ Also in Sweden, about 100 bus fires, or about 1% of the entire fleet, occur annually where the rescue service must extinguish the fire. About 5% of them lead to a complete burn-out of the buses.²⁵ Another study by the Norwegian Public Road Administration and the Swedish Road Administration also confirmed that as many as one in every 100 buses is involved in a fire incident each year.¹¹ On the positive side there has been a gradual increase the last years in the number of buses with automatic extinguishing systems in the engine compartment in Sweden. As late as in August 2019 over 95% of all buses in Sweden, with a total weight of more than 10 tons, had such extinguishing systems installed²⁶.

Despite having a low frequency, there are bus fires resulting from a high-impact accident, which often involve multiple fatalities. A non-exhaustive list with examples of bus fire is given in Table 1. Commonly, passengers can leave the bus in time and bus fires are usually rarely accompanied with severe injuries. However, particular accidents, in which the fire enters the passenger compartment, resulted in an extremely rapid-fire propagation and a high number of fatalities. One could imagine even worse conditions, in the case where the fire occurs in a covered structure or in a tunnel. Firefighter interventions becomes more difficult in such conditions where visibility is reduced. In addition, they have to ensure that the fire does not spread beyond the bus. If there are several buses burning, it becomes even more complicated.

Many involved passengers in all the above-mentioned accidents were most likely to be unconscious or physically impaired when the fire broke. Consequently, the time necessary for evacuation of the

passengers becomes much longer than the time available for tenable conditions to be reached. In addition to the consequences on life safety, this brief review has shown that bus fires can also have significant financial consequences especially when they occur in bus depots, see Table 1. The property loss and the cost due to business and traffic discontinuity can be important. In addition, the development of new technologies for transportation means, such as electrical vehicles or hydrogen as fuel are another potential fire risk, not yet visible in statistics. As an example, the French transportation authority RATP announced in April 2022 to temporarily withdraw from operation 149 electric buses, after a second fire occurring in a month in Paris. They represent a third of Paris' transportation fleet of electric buses.³⁷

3.2 | Accidentology

From literature, even if ignition sources are not reported in case of a large bus fire, collisions were often the leading cause of vehicle fires that resulted in multiple deaths.¹¹ The most common location for the fire to start is however in the engine compartment. According to Rakovic et al.¹¹ two third of all bus fires are reported to start in the engine compartments of the buses. Other studies estimate that 40%–60% of all fires start in the engine compartment. Usually, the cause of a fire in a bus is related to an electrical fault. The other two main reasons for bus fires are an increased friction in a wheel resulting in smoke and heat production, and leakage of oil or fuel.^{4,26,27,38} Another study reports that engine and

TABLE 2 UN regulations related to fire safety of buses.

UN-ECE-R 36 ³⁹	Uniform provisions concerning the approval of large passenger vehicles with regard to their general construction (incl. fire extinguisher, fuel container, and fuel feed pipe)
UN-ECE-R 67 ⁴⁰	Uniform provisions concerning the approval of: I. Specific equipment of vehicles of category M and N ^a using liquefied petroleum gases in their propulsion system. II. Vehicles of category M and N fitted with specific equipment for the use of liquefied petroleum gases in their propulsion system with regard to the installation of such equipment.
UN-ECE-R 107 ⁴¹	Uniform provisions concerning the approval of category M2 or M3 ^b vehicles with regard to their general construction (incl. fire extinguisher, engine compartment and allowed materials in the engine compartment, heat sources, electricity).
UN-ECE-R 110 ⁴²	Uniform provisions concerning the approval of: I. Specific components of motor vehicles using compressed natural gas (CNG) in their propulsion system. II. Vehicles with regard to the installation of specific components of an approved type for the use of compressed natural gas (CNG) in their propulsion system.
UN-ECE-R 118 ⁴³	Uniform technical prescriptions concerning the burning behaviour of materials used in the interior construction of certain categories of motor vehicles.

^aCategory N: vehicles carrying goods.

^bAccording to the UNECE Regulations buses are defined as being vehicles belonging to one of the following categories:

generator compartments, running gear, wheel areas, and electrical enclosures are where almost 60% of vehicle fires occur.¹¹ This is also reported in a Swedish investigation on four bus fires¹¹ that showed that the fires have started in the engine compartment in two cases, in the frame at the rear of the bus in one case and in the luggage compartment in one case. When ignition occurred, the fire spread was in most of the cases very fast.¹¹ The fires propagated quickly to the passenger compartment, leading to extensive damages. In some incident, it is reported that bus drivers had not enough time or capacity to extinguish the fires and that they were surprised how quickly the fire developed and spread to the entire bus. When the fires reach the passenger area, they are likely to engulf the entire vehicle, threatening passengers' lives or reducing the time needed to evacuate.

4 | STATUS OF REGULATIONS, FIRE TESTING, AND LIMITATIONS OF THE METHODS

An overview of the applicable fire regulation for buses and coaches in Europe and their limitations is addressed.

4.1 | Current regulation (Europe)

Safety requirements for motor vehicles are internationally regulated by the UNECE (United Nations and their Economic Commission for Europe) to harmonize international economic standards under the guidance of the United Nations. These regulations include: Regulation 34 for the protection of liquid fuel tanks, Regulations 67 and 110 for gas fuel cylinders, Regulation 107 for fire safety requirements for buses and coaches, and Regulation 118 for requirements and test methods for bus interior materials. Table 2 provides an overview of UN regulations related to fire safety of buses.

- Category M2—Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes.
- Category M3—Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass exceeding 5 tonnes.

For vehicles of category M2 and M3 having a capacity exceeding 22 passengers in addition to the driver, there are two classes of vehicles to which they belong:

- Class I—Vehicles constructed with areas for standing passengers, to allow frequent passenger movement.
- Class II—Vehicles constructed principally for the carriage of seated passengers and designed to allow the carriage of standing passengers in the gangway and/or in an area which does not exceed the space provided for two double seats.

For vehicles of category M2 and M3 having a capacity not exceeding 22 passengers in addition to the driver, there are two classes of vehicles:

- Class A—Vehicles designed to carry standing passengers; a vehicle of this class has seats and shall have provisions for standing passengers.
- Class B—Vehicles not designed to carry standing passengers; a vehicle of this class has no provision for standing passengers.

Existing classification for M2 and M3 vehicles are illustrated in Table 3.

4.2 | Introduction to fire testing for road vehicles

Fire safety regulations for road vehicles are fewer compared to other modes of transport. This is because it is generally possible to immobilize the vehicle and escape in the event of a fire. However, this reasoning has its limits, particularly in the event of a fire outbreak following an accident or a fire starting in a tunnel.

The materials used in the interiors of private motor vehicles and coaches must mainly undergo a horizontal flame propagation test

TABLE 3 Classification from M2 and M3 vehicles (simplified).

Category	Mass	Class	Number of seats	Passenger conditions
M2	<5 tons	A	Between 8 and 22	Principally standing
		B		Exclusively seated
		I	>22	Principally standing
		II		Principally seated
		III		Exclusively seated
M3	>5 tons	A	Between 8 and 22	Principally standing
		B		Exclusively seated
		I	>22	Principally standing
		II		Principally seated
		III		Exclusively seated

according to ISO 3795⁴⁴ or the American method FMVSS 302,⁴⁵ which was developed within the United States in the sixties by the National Highway Traffic Safety Administration (NHTSA). The purpose of the method was to reduce the risks associated with smokers. This mainly concerns the materials present on the surface of the passenger compartment. For public transport vehicles other than low-capacity vehicles, the sound insulation materials of the engine compartment must also undergo these tests. The test consists of subjecting a material placed horizontally to a small flame and measuring the speed of horizontal propagation of the flame front. This test, which is very mild, is said to be of the first generation. It may optionally be supplemented by a dripping test in the event of the presence of drops with potential to ignite a second fuel. Then there are additional specifications applicable, for example, to electric cables or ashtrays.

In public transport, the national and European regulations present requirements on the choice of materials for the interior spaces of vehicles containing more than nine people and distinguish urban buses from coaches. Urban buses of more than 22 people are not subject to any directive on the choice of materials, but must comply with manufacturers' technical specifications based on ISO 3795 or FMVSS 302. For coaches with more than 22 seats (public transport vehicles for seated persons, known as Class II and III and not low capacity), horizontal flame propagation tests, and dripping tests are considered, depending on the material and its use.

4.3 | Material tests applicable for buses

The fire tests for bus interior materials in the EU are similar to fire tests for interior materials of road vehicles around the world since they are all based on the same test method. The methods are based on the test method FMVSS 302 as described above. The purpose of introducing the test originally, was to reduce vehicle fires, especially those originating in the interior of the vehicle from sources such as matches or cigarettes, although vehicle fires are mostly the results of defects in the engine compartment, collisions, or defects in electrical and electronic equipment. Since introducing the fire test, plastic materials have become basic materials in the automotive industry. But the

flammability and the burning behaviour of plastic materials have not yet been considered in the fire safety requirements for materials. In a modern bus, the fire load of plastic parts installed in the passenger compartment is very high.

Fire tests for vehicle interior materials according to the ECE Regulation No. 118 are:

- Test to determine the horizontal burning rate of materials (Appendix 6 of UN ECE R 118)
- Test to determine the melting behaviour of materials (Appendix 7 of UN ECE R 118)
- Test to determine the vertical burning rate of materials (Appendix 8 of UN ECE R 118)

The original fire test for interior materials of buses was a horizontal test procedure according to Appendix 6 of UN ECE R 118 to limit the horizontal burning rate of a small flame. The principle of the test is: A sample is held horizontally in a U-shaped holder and is exposed to the action of a defined low-energy flame for 15 s in a combustion chamber, the flame acting on the free end of the sample. The test determines if and when the flame extinguishes or the time in which the flame passes a measured distance. Five specimens shall be tested in their end-use orientation.

Drapes, жалюзи, hangings and, after recent amendments, all vertically mounted materials must pass an additional test according to Appendix 8 of UN ECE R 118, which limits the vertical burning rate. During the test procedure, a 40 mm burner flame is directed towards the bottom edge for 5 s. If the specimen does not ignite, a next specimen must be exposed for 15 s. Along the sample, marks of a height of 220, 370, and 520 mm are noted. The requirements of the test are passed if the fastest vertical burning rate between both lower marks is less than 100 mm/min or if the flame extinguishes before reaching the last measuring point.

As a mean of approaching the bus requirements with the more elaborate prescriptions for trains and ships, a recent revision of Regulation No. 118 allows the use of the test method ISO 5658-2, lateral spread on building and transport products in vertical configuration.

Ceiling materials and bordered parts, including all materials located 500 mm above the seat must pass an additional drip test which is focused on the melting behaviour of the material. Principle of



FIGURE 1 Dripping test (Appendix 7 of UN ECE R 118).

TABLE 4 Evolution of bus fire safety regulations.

Topic (provision)	Status (scheduling)	Part of the equipment starting: new approval/ registration
Engine compartment with fire detector (ECE-R 107)	Adopted (WP. March 29, 2010)	December 31, 2012/ December 31, 2013
Fire behaviour of bus interior (electrical cable, capability of insulation materials to repel fuel) (ECE-R 118)	Adopted (WP. March 29, 2010)	December 9, 2012/ December 09, 2015
Fire and/or smoke detector in enclosed compartments (except luggage compartment) (ECE-R 107)	Adopted (WP. November 29, 2011)	July 26, 2014/ July 26, 2015
Fire behaviour of bus interior (fire tests in installation position, material tested according to ISO 5658-2 allowed without further testing) (ECE-R 118)	Adopted (WP. November 29, 2011)	July 26, 2016 (components) and July 26, 2016 (complete vehicle)/ July 26, 2017
Fire suppression system in engine compartment (ECE-R 107)	Adopted (WP. July 11, 2016)	June 18, 2018/ June 18, 2019



FIGURE 2 Fire test according to Appendix VI of UN ECE R 118, on a rubber material fulfilling the requirements.

the test according to Appendix 7 of UN ECE R 118: A sample is placed in a horizontal position and is exposed to an electric radiator. A receptacle is positioned under the specimen to collect resultant drops. Some cotton wool is put in this receptacle in order to verify if any drop is flaming. In the drip test the specimen is located on a horizontal grate which is fixed 300 mm over the bottom and 30 mm below an electrical heater which radiates a thermal intensity of 30 kW/m^2 to the specimen. During the test period the ignition and the drip behaviour of the specimen and the underlying cotton ball are monitored for 10 min. If the specimen ignites in the first 5 min of the test the electrical heater must be immediately removed within 3 s until the flame vanishes. After these five test minutes or after the flame vanishes, the specimen is radiated for another 5 min without stops when the sample ignites again. The requirements are fulfilled if the cotton ball was not ignited by burning drips during the test (Figure 1).

4.4 | Limitation of the existing method

Although fire safety regulations of buses have been amended several times, as Table 4 shows, fire safety requirements for interior materials of buses are still on a lower level than material requirements for other transport sectors.

The test method according to R 118, Annex 6, the horizontal burning test, is a deficient method, where almost all materials pass the requirement. The only requirement from the method is the burning rate in the material, expressed as mm/min. There are no requirements of burning droplets, smoke production or fire intensity. Figure 2 shows a fire test of a rubber material with a burning rate of 42 mm/min, well approved since the requirement is 100 mm/min. However, during the test, a lot of dark smoke was produced, which filled the cabinet. In addition, large pieces of melted and burning material fell

FIGURE 3 Cardboard sample after testing according to R 118, Annex 6. Safety-match, 100 mm long, before testing.

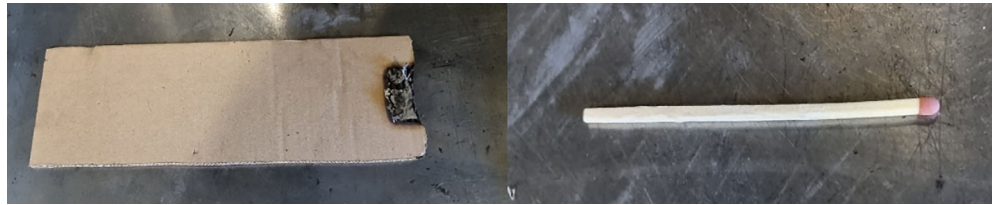


FIGURE 4 Fire testing of a PC/ABS material according to R 118, Annex 8.



from the test sample, creating a pool fire at the bottom of cabinet. The smoke and the burning droplets are both considered as unsafe in fire safety engineering and can lead to fire spread and smoke-related injuries, or even death.

Fire testing with the same equipment of a cardboard, Figure 3, showed that the sample self-extinguished before the first marker, thus considered to have no burning rate and therefore fulfil the requirements. Another material evaluated with the method was a safety-match, which is developed to burn, showed a burning rate of 83 mm/min, thus also approved by the standard. None of these materials would be used nor acceptable for interior materials in a bus, but the tests results illustrates that even materials considered as highly flammable will pass the R 118, Annex 6 test.

The test method according to R 118, Annex 8, the vertical burning test, is considered as a tougher fire test, in comparison with the horizontal burning test. This method also measures the burning rate of the material, and does not deal with smoke production, melting material or burning droplets. Fire testing of a PC/ABS material, commonly used as interior material in buses, showed that the material melted and dropped into a large burning piece of material under the sample. The burning is shown in Figure 4. As a result, the progressive fire at the sample stopped. In addition, dark smoke was produced. As

the material melted and the burning part dropped from the sample, the flames extinguished at the sample, resulting in an approved fire test according to the regulation.

4.5 | Further aspects on the need for appropriate fire regulations

Low-performing interior materials increase the probability for complete burnout of buses. In addition to putting at risk the life safety of passengers, a complete burnout incurs substantial environmental impacts⁴⁶ as well as results in the prematurely disrupted life cycle of the bus. A full burn out of the bus also leads to higher economical losses for owners and/or insurance companies. In a similar manner, the environmental and economic losses may be very high when a fire, due to sub-standard fire requirements, is allowed to spread in and between buses in, for example, parking or bus depots. Examples of such multiple bus fires are the fire on the Bottrop bus depot in Germany 2011 (69 buses), see also Table 1. It is not unusual that buses that have been parked in a depot are ignited. This may have several reasons such as charging (electric buses), fan cooling switched off (internal combustion engines), or arson, for example. Fortunately,

these type of fires in parked buses, or multiple parked buses, rarely lead to fatalities. Fire spread in assemblies of buses parked in a hangar or bus depot, may be amplified by enclosure fire effects (enhanced feedback of energy from the fire gases to the fuel). These effects can increase spread, that is the number of vehicles involved in the fire, and the severity of fires, resulting in major property loss on the building itself.^{47,48} A related and more cumbersome area is bus fires inside tunnels. Here the importance of the damage to the vehicle(s) and tunnel is only second to the substantial risk for fatalities. Bus fires in tunnels would typically occur for buses in operation, with passengers and driver inside the bus. Tunnel fires are aggravated by enclosure effects and the decreased walking speed of evacuees. Due to enclosure fire effects a tunnel bus fire is not necessarily initiated in the bus itself but can also occur due to heat transfer from other ignited vehicles, for example, due to a collision, to the bus in a queue that is created as a result of accidents. Especially in the case of alternative fuels⁴⁹ such as CNG it is important that the combustion of the interior bus material itself does not add thermal load to the fuel, which could result in devastating jet fires or even explosions inside the tunnel.

In the future, new threats, regarding fire safety of the vehicle, will appear as the development of new materials and products proceeds. New types of buses with other fuels will most likely be developed. Examples of new fuel types are gas-powered buses, E-powered buses, pure e-operation, hybrid with e-component, and hydrogen/fuel cell + e-operation. In addition to the development of other fuel systems, the material selection for interior parts will also be developed.

The requirements of the materials, such as impact on environment, health, and sustainability as well as cost, will have a major impact. An example of new materials, which are lightweight, are alloys of Aluminium and Magnesium, which burn well in a developed fire. Overall, there are two main aspects that need to be considered: ignition of technical parts/engine and the ignition in vehicle interior.

Fire characteristics and mitigation recommendations are different for the two aspects, and they should be both considered.

5 | AN ADAPTED FIRE STRATEGY

To remedy the shortcomings of the current requirement, additional measures that need to be implemented are proposed, and concern both material, fire tests, and fire scenarios.

5.1 | Reference scenarios for fire and evacuation

The ignition scenarios in road transportation typically consider ignition from small fire sources such as smoker articles. Standards like FMVSS 302 have been developed in such perspective and do not consider more intense fire sources, for example, short-circuit with more and more electrical appliances including leisure equipment, fire penetrating from the engine compartment, or wheel well fires penetrating into the passenger compartment via windows. Consequently, ignition

scenarios are not adapted nowadays to the current fire sources, and the tests performed do not cover these.

The general procedure in case of a bus fire is to stop the vehicle and to evacuate the persons as soon as possible. It is generally accepted that people must evacuate from a bus by themselves, and they cannot rely on being rescued by firefighters. Indeed, in most bus fires, the arrival of firefighters is usually to secure the area and either to extinguish the developed fire or to make sure that the fire will not re-ignite. This means that the bus should be designed to guarantee tenable conditions for evacuation of its passengers during a fire, which is not currently the case. In contrast to other means of transport, such as planes or trains, this is a unique situation. The evacuation scenarios are not explicit but shall consider the time to stop and to evacuate. In addition, in the case of a collision, passengers in buses rarely use seat belts and thus can be severely injured, or the shock can lead to damages to exit doors. No employees are specially dedicated to assist people in evacuation such as steward or controller, and the type or age of the passengers are not considered, such as in the case of coaches operating in long-distance during the night, with sleeping passengers, or due to an ageing population.

By analogy, aircraft regulations state a complete evacuation of the plane on ground in less than 90 s, with half of the doors remained closed. Railway scenarios consider either 4 min in case of urban applications, which considers interstation delay plus evacuation delay, or 15 min for main lines, where evacuation in a relative place of safety on-board is considered during first minutes, then a containment of fire for 15 min, considered facing running capability of 20 km, for example, to go out in case of tunnel scenario. As a consequence, there is a lack of predefined evacuation scenarios and objective in road transportation.

For example, the fire safety strategies for railway vehicles are defined in EU interoperability directives and supported by the European standard EN 45545 series relating to fire protection in railway vehicles. All these aspects have been defined during pre-normative research work in the nineties.^{50,51}

The European standard EN 45545-1⁵² set the protection objectives, which are:

- To prevent fires occurring due to technical faults and due to equipment design or vehicle layout,
- To minimise the possibility of ignition of materials installed on railway vehicles due to accidents or vandalism,
- To detect a fire if it should occur,
- To limit the spread of fire by specification of materials according to their operational categories and by measures for containment,
- To minimise the effects of fire in terms of heat, smoke, and toxic gases on passengers or staff through the specification of materials installed on railway vehicles,
- To control and manage a fire, for example by means of fire detection, suppression, and/or emergency energy shut down.

The ultimate objective in the event of a fire on board is to allow passengers and staff to evacuate the railway vehicle and reach a place

of safety.⁵³ To reach these objectives, vehicles are classified according to the following Operation Categories:

- Operation Category 1: Vehicles for operation on infrastructure where railway vehicles may be stopped with minimum delay, and where a safe area can always be reached immediately.
- Operation Category 2: Vehicles for operation on underground sections, tunnels, and/or elevated structures, with side evacuation available and where there are stations or rescue stations that offer a place of safety to passengers, reachable within a short running time.
- Operation Category 3: Vehicles for operation on underground sections, tunnels, and/or elevated structures, with side evacuation available and where there are stations or rescue stations that offer a place of safety to passengers, reachable within a long running time.
- Operation Category 4: Vehicles for operation on underground sections, tunnels, and/or elevated structures, without side evacuation available and where there are stations or rescue stations that offer a place of safety to passengers, reachable within a short running time.

They are also classified under the following Design Categories:

- A: vehicles forming part of an automatic train having no emergency trained staff on board
- D: double decked vehicles
- S: sleeping and couchette vehicles
- N: all other vehicles (standard vehicles).

Finally, the requirements are a function of the hazard levels (HL 1–HL 3). These hazard levels depend on the Design Category and their Operating Category, which both affect the evacuation strategy. Three hazard levels HL 1–HL 3 are defined, HL 1 being the lowest requirement and HL 3 being the highest.⁵⁴

The performance of all the products used in a railway vehicle is determined with respect to ignitability, flame spread and the amounts of heat, smoke, and toxic fumes produced. These reaction to fire tests aim at qualifying and classifying the products according to their final applications which are separated into groups, including structural products, seats, cables, and non-listed items. Each of these product groups are required to meet a specific set of performance requirement levels. Each requirement has a corresponding series of test performance criteria imposed for each fire risk levels HL 1–HL 3. The test methods used depend on the product under investigation. For instance, for the same use, the requirements will be more severe for a material fitted to HL 3 equipment than for a material fitted to HL 2 or HL1 equipment.

In the aeronautical sector, the fire safety strategy is adapted to its particular conditions. While there are no regulations set by international bodies for aircraft, the specifications issued by the Federal Aviation Administration of the United States are the most widely used. For fire resistance, the requirements are detailed in the Federal

Aviation Regulations (Appendix F of FAR 25).⁵⁵ The objective of these regulations is to limit the flammability of materials in flight and to save time for evacuation in the event of emergency landing. The performance objectives for post-crash scenarios specified in the aeronautical field are 90 s for evacuation and 4 min for the arrival of help. Additionally, all staff are trained to extinguish a fire occurring in a cabin. Therefore, in flight scenarios, it is expected that the staff is able to extinguish the fire very quickly, despite the high ignitability requirements. If analogies with bus fires are considered, then what are the expected evacuation delays without the help of staff? In the same way, one should consider upcoming technological threats such as automatic driven buses, as it highlights the questions of detection alarm and evacuation without any staff.

In the maritime sector, safety of ships over 24 m long and over 500 gross tons (GT) is regulated by the International Maritime Organization (IMO).⁵⁶ A ship is made up of different areas designed and compartmentalized so that the fire does spread from one to the other. Active and passive fire safety systems are used to limit the spread of fire. Materials on escape routes must undergo reaction to fire tests (surface spread of flame, opacity, and toxicity, in addition to other requirements for upholstery and curtains). If they are used for structural purposes, or if they contribute to the fire compartmentalization, they must also be noncombustible and undergo fire resistance tests.

For illustration, all the fire tests for interior materials of the different transport means are listed in Table 5.

Although city buses, trams, long-distance buses (coaches), and trains are operating similarly, the requirements on the used materials are very different. A comparison of required fire test for materials in different transport sectors can be seen in the following table.

This comparison shows that most of the required fire tests for interior materials of other transport sectors are not mandatory for buses and cars. The horizontal fire test, which is the fundamental part in the fire safety requirements for buses, is not requested in the other transport sectors. All other transport sectors require the stricter vertical fire test as minimum which ensures a basic fire safety for all used materials on a higher level. Neither the heat release rate nor the smoke production or smoke toxicity are considered in the regulations for bus interiors. This is the case although heat release is a key factor for fire propagation. Smoke production and toxicity can result in incapacity and prevent escape of passengers. In contrast to the situations for trains extra fire safety requirements for bus seats (e.g., against arson) or flooring materials do not exist.

For all the above-mentioned sectors, fire safety standards are set to fit with an adapted fire safety strategy and when gaps or shortcomings are identified, usually after a fire incident, they are addressed in their revisions. In contrast, the bus sector has remained status quo for decades. It is common knowledge in the fire safety community that the ISO 3795⁵⁷ test method is inadequate for discriminating between different levels of fire performance. Multiple initiatives have been taken to the Working Party on General Safety Provisions (GRSG) at United Nations Economic Commission for Europe (UNECE) to address this issue.⁵⁸ The most recent amendment to the Regulation No. 118 was made in 2012⁴³ to the ISO 3795 test for bus interior

TABLE 5 Overview of fire tests for interior materials in different transport means.

	Cars	Buses (ECE R 118)	Rail vehicles (EN 45545-2)	Ships (SOLAS Chapter II-2)	Aircraft (FAR/ JAR/ CS 25.853)
Horizontal burning rate	ISO 3795 (same test as in Appendix VI of UN ECE R 118)	Appendix VI (horizontally mounted components)	No test	No test	FAR/JAR/CS 25.853 b (5) (cabin and cargo compartment)
Vertical burning rate	No test	Appendix VIII (vertically mounted components)	EN ISO 11925-2 (Filter materials)	ISO 6940/41 (drapes and hangings)	FAR/JAR/CS 25.853 b (4) (cabin and cargo compartment)
Melting behaviour	No test	Appendix VII (ceiling materials)	No test	No test	No test
Heat release rate	No test	No test	ISO 5660-1 (most materials)	ISO 5660-1/ISO 9705-2 (fire-restricting materials in high speed crafts)	FAR/JAR/CS 25.853 (d) (cabin compartment)
Flame spread/ burning through	No test	No test	ISO 5658-2 (most materials)	IMO FTP Code Part 5	FAR/JAR/CS 25.855
Smoke density	No test	No test	ISO 5659-2 (most materials)	ISO 5659-2 (most materials)	FAR/JAR/CS 25.853 (d) (cabin compartment)
Smoke gas toxicity	No test	No test	ISO 5659-2 (most materials)	ISO 5659-2 (most materials)	BSS 7239/ABD 0031 (cabin compartment)
Calorimeter test for seats	No test	No test	ISO 9705-2 (passenger seats)	ISO 8191-1/-2 (upholstered furniture)	FAR/JAR/CS 25.853© (upholstered furniture)
Flooring	No test	No test	ISO 9239-1 (flooring materials)	IMO FTP Code Part 5 (flooring materials)	FAR Part 25 Appendix F Part VI (flooring materials)

materials, where in addition to testing specimens while oriented horizontally, they shall also be oriented vertically. However, as fires are often initiated by a fire in the engine compartment or in a tyre, small-scale methods as ISO 3795 have limited benefits and can hardly simulate these conditions.⁵ Furthermore, this test method only covers ignitability criteria but is not sufficient to assess the fire behaviour of products used in vehicles to include flammability, heat release, smoke opacity, and smoke toxicity. Although feedback shows that once the flames reach the passenger space, fire spread occurs quickly.⁵⁹ Hence, there is a need to bridge the gap between the different fire safety levels in mode of transport.

Studies have shown that in case of a fire in a bus, the time for evacuation before tenability conditions are compromised will range in about 4–5 min,⁶ meaning that evacuation is not adapted for sensitive populations, such as persons with reduced mobility (PRM), children and elderly. From the first real scale bus fire test mentioned in Section 2, it was shown that although the fire started in the engine compartment and did not spread into the passenger cabin, the air in the passenger compartment became toxic in a few minutes, meaning that safe passenger escape could not be guaranteed.⁶ Furthermore, the classical RSET/ASET approach to evaluate safe evacuation could not always be satisfied, even more so when the evacuation occurs in a compartment that can be already partially filled with smoke. During

the two fire tests performed by SP with CNG buses in the autumn of 2012 to reproduce a bus fire in Helsingborg,⁶⁰ it was shown that a fire in the engine compartment can develop very quickly, from a limited local fire to one creating critical conditions for passengers on the bus. In one of the tests performed on a city bus with the engine not running, high CO concentrations were measured at one of the doors after only 3 min 13 s, while evacuation of the passengers took 1 min 28 s with all the doors available for evacuation. However, it was shown from videos of the original accident, that the spread of the fire in the accident was considerably faster than in the tests. In addition, the evacuation time can increase if a door is malfunctioning or in the presence of PRM.

Even worse, in case of a fire combined with an accident, evacuation of sensitive population by themselves would even be impossible. This means that any major accident that includes a fire will most likely result in fatalities (e.g., Hanover bus fire 12 on November 4, 2008).

It is worth noting that a city bus is not different in use from a tramway, while the fire performance of their interior products is completely different. It should also be noted that the severity of the rules applicable to public transport is very low compared with those required in other modes of transport and close to those for individual vehicles. Studies have been performed in Norway and Sweden to increase these requirements in Europe but have so far remained

unanswered.^{1,3,4,6} In Germany, the materials present in buses were tested and compared to the railway reference which demonstrated the strong difference in performance levels between these two benchmarks.^{2,59} None of the materials present in the buses studied could pass the criteria required for the lowest hazard level from the railway sector.²

The situation is even more worrying for coaches and pan-European lines that include sleeping travellers, which are increasing in popularity. The fire safety measures for testing the interior material should be improved to fit with an adequate fire safety strategy and allow passengers to evacuate the bus by themselves or by the help of external rescues, before the tenability conditions are compromised in case of a fire or a fire combined with an accident.

Extensive research was done to define adapted thresholds for a classification system from products used on trains, taking into consideration relevant fire scenarios and parameters influencing the fire safety, like design, ventilation, and their effects on people.⁶¹ Hence, one could easily transpose existing standards from the railway to the bus application.

5.2 | Covering all fire scenarios

Looking at existing studies,^{1,2,9} it seems that many products available in the interior of the bus constitute an important fuel load inside the passenger compartment, making its fire development very important. Those are seats, ceiling coverings, wall covers, and curtains. A fire performance is also necessary for the engine separation, as most fire incidents start from the engine compartment. Similarly, the floor complex (not just floor covering) should be evaluated as it makes a separation with the luggage area, where the fuel load can be important. A research report six identified weaknesses in the fire resistance of separating walls between the passenger and engine compartment in particular, but also the wheel houses and surrounding areas. The adequate rating in terms of fire performance for the fire barrier used as partition can be different depending on the risk zones as well as the burning behaviour and the fire intensity. Performances required in terms of integrity were comprised between 10 min (luggage compartment, electric distribution box area, remaining spaces under bus floor or space for electrical devices) and 30 min for the engine compartment.

With alternative fuel technologies now increasing (hydrogen, electrical etc.), fire threats from inside of the bus should be minimised to avoid the development of a larger fire and becoming a severe threat to the hydrogen or LG tank over the ceiling. Protecting the inside of a bus from important fire development will reduce the risk of an early end of life of a bus.

It is therefore important to define relevant fire scenarios that can cover all types of bus fires. A first attempt would be using existing classifications from UNECE⁶² and to adapt them to the different fire safety level, which would decline the different requirements. Vehicles with standing passengers often operate in the city and at relatively low speed (e.g., city bus). Hence it is assumed that in case of a fire, the

vehicle could stop easily and its passengers would be able to reach an escape more easily than when in a seated vehicle. The only drawback is that such a vehicle is often packed, hence it could require additional time to evacuate all the passengers. On the other hand, seated vehicles can operate on any type of roads (highways etc.) at potentially higher speeds than city buses, hence they cannot easily stop and are more prone to being involved in major accidents. They will have more fuel load due to the higher number of seats and the evacuation becomes more difficult due to the obstacles. In addition, there is a possibility of coming across sensitive populations (sleeping passengers, PRM, children, etc.).

Therefore, we propose that vehicles with principally standing passengers (M2 & M3 Class A and Class I) require a lower level of safety than those that are principally/exclusively seated vehicles (M2 & M3 Class B or Class II and III), as illustrated in Table 6. Two Hazard Levels (HL) can therefore be assigned for standing and seated buses and compared to existing HL 1–2 for trains, respectively.

The requirements for each hazard level will be introduced in the next section.

5.3 | Adapted fire tests

The fire strategy recommended by the authors uses the analogy in fire scenarios and in evacuation paradigms than the one used in urban rail transportation, with adapted severity. The ignition shall consider more intense sources. The objective of 4 min covering stopping the bus and accomplishing total evacuation is also kept. To achieve such an objective, propagation shall be limited. Heat release, as well as smoke opacity and toxicity shall remain at low levels.

This means that all materials accepted on-board trains can be easily used in road transportation. The requirements proposed by the authors are limited to few categories that we estimate urgent to be covered. As railways requirements have been applied since the seventies, they cover much more materials. In our proposal, we limit to main vertical surfaces, ceiling materials, floorings, seats, and curtains. These materials represent the majority of the needs to cover the risks for scenarios inside the passenger compartment.

For practical reasons, materials that are non-combustible (e.g., classified as A1 conventionally or according to EN 13501-1) are accepted without further tests. Materials presenting total exposed surfaces less than 0.2 m² are also excluded.

Two hazard levels are defined (see Table 6). HL A covers principally standing buses, as they are supposed to be evacuated easily compared with seated coaches. For seated coaches, the requirements are defined as HL B. The proposed fire tests are inspired from existing standard test methods such as EN 45545-2. When materials are used in multilayer compositions, they shall be assembled and tested over representative substrate. Default substrate is metallic sheet, 2 mm steel.

The main differences with railways are a very limited set of requirements and number of materials to be tested. Requirement for main surface materials such as walls and ceilings is inspired from requirement R1 of EN 45545-2. For such products, ignitability is

Passenger conditions	Category	Class	Proposed hazard level
Principally standing	M2/M3	A	HL A
		I	
Principally/exclusively seated	M2/M3	B	HL B
		II	
		III	

TABLE 6 Proposed safety levels for M2 and M3 vehicles.

TABLE 7 Proposed test methods and thresholds.

Product type	Test parameter	Test method	Measured parameter and unit	Proposed maximum threshold for buses		Existing maximum threshold for railways in Europe	
				HL A	HL B	HL 1	HL 2
Interior main surfaces (wall, ceiling, etc.)	Ignitability	EN ISO 11925-2	Burnt length	<150 mm/60 s (15 s flame application)	<150 mm/60 s (30 s flame application)	<150 mm/in 60 s (30 s flame application)	<150 mm/60 s (30 s flame application)
	Flame spread	ISO 5658-2	CFE	20	20	20	20
	Heat release	ISO 5660-1 @50 kW/m ²	MARHE	-	90	-	90
	Smoke production and toxicity	ISO 5659-2 + EN 17084 met.1 @50 kW/m ²	DS4 VOF4 CITg	600 1200 1.2	300 600 0.9	600 1200 1.2	300 600 0.9
Curtains	Ignitability and flame spread	EN 13773	-	Class 3–4	Class 1–2	Same as interior main surfaces	Same as interior main surfaces
Flooring	Flame spread	EN ISO 9239-1	CHF	4.5	6	4.5	6
	Smoke production and toxicity	ISO 5659-2 + EN 17084 met.1 @25 kW/m ²	Dsmax CITg	600 1.2	300 0.9	600 1.2	300 0.9
Upholstery	Heat release on full seat	EN 16989	MARHE	80	55	80 ^a	55 ^a
	Smoke production and toxicity on components	ISO 5659-2 + EN 17084 met.1 @25 kW/m ²	Dsmax CITg	200 0.75	200 0.75	200 0.75	200 0.75

^awith additional requirements for components.

tested according to EN ISO 11925-2 with differences in application time between HL A and HL B. Flame spread is assessed through ISO 5658-2 test, with a requirement of critical heat flux similar to railways or ships. Additional requirement on heat release rate is asked for HL B. Smoke opacity and toxicity are considered with requirements similar to railways. Requirements for curtains cover ignitability and flame spread according to EN 13773, which is the European standard test method for curtains. Requirements for floorings are inspired from requirement R10 of EN 45545-2. Requirements for upholstery (including seats and berths) are adapted from requirements R18 and R20 of EN 45545-2. Ignitability, flame spread, and heat release are covered by a single seat test, where main components of seat and backrest are tested as a small representative cushion for smoke opacity and smoke toxicity. For upholstery furniture, we propose to evaluate the heat release rate on a full-scale seat mock-up, while in the

railway application, small components and full-scale mock-up are tested, in addition to other requirements. All these requirements proposed are summarized in Table 7. This proposal results in fire testing requirements for materials that are similar and comparable to the other transport sectors as presented in Table 5. This proposal can be refined and optimised through further research and experimental tests correlating requirements with fire scenarios and tenability conditions. Nevertheless, the current proposal shall improve the existing conditions using products that are available on the market.

6 | CONCLUSION

Buses and coaches have been, and still are, the bad egg in fire safety compared to other transport means, and also compared with the

safety level in buildings! A striking example was shown in this work where both cardboard and safety matches were tested according to the horizontal burning rate test in UN ECE Reg No 118, annex 6. This test method is the main method qualifying interior materials in the passenger compartment of buses and coaches. The method is also known as FMVSS 302 and ISO 3795 and is the qualifying test also for materials in cars. Neither cardboard nor safety matches are in any conceivable way fire safe materials—still they passed the test.

Despite having a relatively low frequency, there are many bus fires resulting from high-impact accidents, which often involve multiple fatalities. Even though there has been some development of the bus fire safety regulations, the current requirements have major shortcomings. The aforementioned requirement for interior materials, Regulation 118, specifically Annex 6 horizontal burning rate, is based on a historical fire scenario from the seventies where the fire was assumed to start in the occupant area. The ignition source was to simulate ignition from a cigarette. However, this ignition scenario is no longer a common cause of a fire. Recent bus fire accidents are instead typically caused by a fire starting in the engine compartment or in a tyre. As a result, the thermal exposure from these fires into the passenger compartment is very large and can ignite interior materials irrespective of their performance in the small-scale fire tests of UN ECE Reg No. 118, and lead to sustained and rapid flaming. The small-scale fire test methods described in UN ECE Reg No. 118 are not useful for these kinds of fire scenarios and need to be replaced by test methods that can assess the reaction to fire of materials when exposed to ignition sources of varying sizes.

Furthermore, the bus fire requirements according to UN ECE Reg No. 118 only deal with fire performance parameters such as ignitability, burning rate, and ignition from burning droplets. There are no requirements related to heat release, smoke production or smoke gas toxicity, even though these parameters are strongly affecting evacuation conditions. A high smoke production will have a direct impact on the time for evacuation and the smoke gas toxicity will affect the passenger's ability to evacuate. In case of a fire combined with an accident, extraction of passengers will rely on waiting for external assistance, which is often incompatible with the time before untenable conditions are reached, mostly in few minutes. Summarizing all these statements related to the deficiency of the current bus fire safety regulation, there is a clear need of an improvement for the fire safety of interior materials of buses, to limit the fire, and smoke spread inside the bus.

The fire requirement standard EN 45545-2, applicable for materials used in railway vehicles, is based on comprehensive pre-normative research conducted during more than a decade. Thorough analysis of fire scenarios, material performance, product end use application, vehicle categories, and operation categories has been used as base for the development of the standard allowing for a safe escape from the vehicles. For interior materials there are requirements on parameters such as the ignitability, the flame spread and the smoke gas toxicity. The present study suggests a similar approach for an extended and revised version of the bus fire regulation, with the buses divided into operation categories and the materials divided into product types. Fire test

methods are selected due to their relevance for each product type. These tests methods are inspired from well-known standard test methods used in other transport applications such as in railways, with simplified test requirements. The level of requirements for each fire parameter related to the fire test method can still be improved by fine-tuning, it will require conducting research on a complete framework assessing the fire scenarios applicable to buses and their related evacuation paradigm. Nevertheless, these standard test methods are extensively used, there are multiple products already available on the market that can fulfil the proposed requirements.

More adequate fire requirements on the interior materials of buses will extend the time with tenable conditions for a safe evacuation in case of fire, and thereby save lives. Also, the time before flash-over in the bus compartment will be longer, giving more time, for example, rescue service operations to evacuate disabled passengers. In addition, the likelihood and the cost for fully fire-damaged buses would also decrease. Finally, the proposed requirement will reduce the risk for fast and excessive thermal exposure on modern energy carriers needed for a more sustainable transport sector, such as batteries and LNG tubes. Thermal overloading on such energy carriers constitutes a major threat to the surroundings of the bus.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data sharing not applicable - no new data generated, or the article describes entirely theoretical research.

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