# Development of a Combined Experimental and Simulative Method for the Assessment of Fire Scenarios in Motor Vehicles

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# Abstract

Road vehicles are common means of transport. Nevertheless, in case of fire the situation within a road vehicle can turn all of a sudden into a severe life-threatening scenario for passengers and drivers. Especially in vehicles having high passenger capacity, this might entail high numbers of injuries or even fatalities as seen in the severe German bus fire which occurred in 2008 near Hanover with 20 fatal casualties.

Fire safety of road vehicles has been a neglected area in recent decades. Modern materials being robust, lightweight and cost-efficient have been established in the automotive sector. But fire safety requirements have been left unchanged although a lot of plastic materials applied in road vehicles provide worse reaction-to-fire behaviour while still being compliant to fire safety standards required. The main fire load in nowadays road vehicles is no longer fuel, but instead consists of plastic components. When burning, these materials do not only release a high amount of heat but also a lot of opaque and toxic smoke. These facts could be proven in fire tests performed for research related to the dissertation at hand which also has been reason for initiating the ongoing update progress of relevant regulations.

When investigating materials of road vehicles the basic questions were, what is the status quo of fire safety performance in road vehicles and how can it be reasonably assessed? To find an answer to these questions, research was conducted to develop '..a combined experimental and simulative method for the assessment of fire scenarios in motor vehicles'.

The latest state of the art in fire safety engineering is marked by adopting numerical CFD simulations which enables integrating flow characteristics entailed by the fire development within the area focused at. Up to now numerical fire simulations have been predominantly applied on environmental investigations in which a coarse cell grid can be used, such as for buildings or industrial halls. However, investigations on road vehicles interior need to take into account a much more complex and intricate design. The approach applied, the fire tests performed as well as the results gained are presented in the dissertation at hand.

# Kurzfassung

Straßenfahrzeuge sind weitverbreitete Verkehrsmittel. Dennoch kann im Brandfall die Situation für Fahrgäste und Fahrer in einem Straßenfahrzeug schnell lebensgefährlich werden. Besonders bei Fahrzeugen mit hoher Fahrgastkapazität kann dies eine hohe Anzahl an Verletzten und sogar Todesfälle zur Folge haben, wie beispielsweise bei einem schweren Busbrand in der Nähe von Hannover mit 20 Todesfällen in 2008 geschehen.

Der Brandschutz bei Straßenfahrzeugen wurde in den letzten Jahrzehnten vernachlässigt. Moderne Materialien, die robust, leicht und kostengünstig sind, haben sich im Automobilsektor durchgesetzt. Allerdings sind die Brandschutzanforderungen unverändert geblieben, obwohl viele der in Straßenfahrzeugen verwendeten Materialien ein schlimmes Brandverhalten trotz Brandschutz-vorschriften aufweisen. Die primäre Brandlast heutiger Straßenfahrzeuge ist nicht länger der Treibstoff, sondern besteht stattdessen aus den Kunststoffkomponenten. Im Brandfall setzen deren Materialien neben großen Mengen an Wärme auch viel dichten und toxischen Rauch frei. Diese Fakten konnten in Brandversuchen für diese Dissertation nachgewiesen werden, welche auch teilweise Grund für die derzeitige Überarbeitung betreffender Regelwerke sind.

Beim Untersuchen der Materialien von Straßenfahrzeugen waren die grundlegenden Fragen, wie der gegenwärtige Stand beim Brandschutz von Straßenfahrzeugen aussieht und wie dieser angemessen bewertet werden kann. Um Antworten auf diese Fragen zu finden, wurde Forschung betrieben, um eine kombiniert experimentelle und simulative Methode für die Bewertung von Brandszenarien in Straßenfahrzeugen zu entwickeln.

Die heutige moderne Technik im Brandschutzingenieurwesen basiert auf Anwendung von CFD-Simulationen, die Strömungseigenschaften aufgrund der Brandentwicklung im untersuchten Gebiet berücksichtigen. Bisher wurden numerische Brandsimulationen vorrangig für Gebiete angewendet, bei denen ein grobes Zellmuster angewendet werden konnte, wie etwa bei Gebäuden oder Industriehallen. Hingegen muss bei Straßenfahrzeugen ein komplexeres und schwieriger abbildbare Umgebung berücksichtigt werden. Die angewendete Methode, die durchgeführten Brandversuche sowie die gewonnen Ergebnisse werden in dieser Dissertation vorgestellt.

# Acknowledgements

First of all, I would like to express my deep gratitude to my doctoral supervisor Prof. Ulrich Krause and to my project and team leader Dr. Anja Hofmann-Böllinghaus for trusting me with a doctoral position at the Federal Institute for Material Research and Testing (BAM), which entailed all these interesting and demanding research topics and becoming a member in their brilliant research team.

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# List of Abbreviations

| | |
|---|---|
| AGW | Maximum allowable concentration |
| ARHE | Average Rate of Heat Emission at time t |
| ATR | Attenuated Total Reflectance spectroscopy |
| CFAST | Consolidated model of Fire And Smoke Transport |
| CFD | Computational Fluid Dynamics |
| CFE | Critical heat Flux at Extinguishment |
| CIT | Conventional Index of Toxicity |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| CS | Certification Specification of the European Aviation Safety Agency |
| $D_s$ | Specific optical density |
| FAR | Federal Aviation Regulations |
| FED | Fractional Effective Dose |
| FDS | Fire Dynamic Simulator |
| FTIR | Fourier Transform Infrared spectroscopy |
| FTP | Fire Test Procedure (Code) |
| GRP | Glass fibre Reinforced Plastic |
| HBr | Hydrogen Bromide |
| HCl | Hydrogen Chloride |
| HCN | Hydrogen Cyanide |
| HF | Hydrogen Fluoride |
| HL | Hazard Level |
| HRR | Heat Release Rate |
| HRRPUA | Heat Release Rate Per Unit Area |
| I | Incident luminous flux |
| ILV | Indicative Limit Values |
| IMO | International Maritime Organization |
| IR | Mid-Infrared |
| JAR | Joint Aviation Requirements |
| LES | Large Eddy Simulation |
| LTD | Linear Thermal Detector |
| MAC | Maximum Allowable Concentration |
| MAK | Maximum workplace Concentrations |
| MARHE | Maximum Average Rate of Heat Emission |
| MLR | Mass Loss Rate |
| MOD | Mass referenced Optical Density |
| $NO_x$ | Nitrous gases |
| OC | Operation Category |
| PA | Polyamide |
| PE | Polyethylene |
| PES | Polyester |
| PP | Polypropylene |
| PU | Polyurethane |
| PVC | Polyvinyl Chloride |
| SBF | Swedish Fire Protection Association |
| SBI | Single Burning Item |

| | |
|---|---|
| $SO_2$ | Sulphur Dioxide |
| SOLAS | International convention for the Safety of Life at Sea |
| SP | Technical Research Institute of Sweden (now RISE) |
| StVZO | German Road Traffic Licensing Regulation |
| T | Transmitted luminous flux |
| THR | Total Heat Release |
| Tig | Time to ignition |
| TLSE | Terminal Lug Sensing Element |
| TRGS | Technical Rules for Hazardous Substances |
| UN-ECE | United Nations and the Economic Commission for Europe |
| VOF4 | Cumulative value of specific Optical densities in the First 4 min of the test |

# 1. Introduction

In the beginning of the dissertation at hand the background and motivation as well as subsequently the aims, objective and structure of the thesis are pointed to.

## 1.1 Background and Motivation

Road vehicles are to be counted to safe means of transport. Nevertheless, in case of fire the situation within a road vehicle can turn all of sudden into a severe life-threatening scenario for passengers. Especially in mass transport vehicles, this might entail high numbers of injuries or even fatalities as seen in the severe German bus fire occurred in 2008 near Hanover with 20 fatal casualties.

The main fire load in nowadays road vehicles is no longer fuel, but instead consists of plastic components mainly used for the interior. While burning these materials do not only release a high amount of heat but also a lot of opaque and toxic smoke. With the increase of interior plastics due to their good mechanical properties as well as their low weight, the question arises whether or not the fire safety in road vehicles is still sufficient. This underlines not only the high importance of fire safety precautions in road vehicles, but also the undeniable need to permanently strive for enhancing them by adopting latest fire safety engineering standards.

The latest state of the art in fire safety engineering is marked by adopting numerical Computational Fluid Dynamics (CFD) simulations which enables integrating flow characteristics entailed by the fire development within the area focused at. Up to now numerical CFD simulations have been predominantly applied on environmental investigations in which a coarse cell grid can be used, such as for buildings or industrial halls. Compared to this, investigations on road vehicles interior need to take into account a much more complex and intricate constellation. For the dissertation at hand this was the reason to research on ’Development of a combined experimental and simulative method for the assessment of fire scenarios in motor vehicles’.

## 1.2 Aims, Objective and Structure of the Dissertation

The overall aim of research work done was to establish current state of the art of fire safety in road vehicles. Therefore several fire tests and numerical simulations were performed. First typical interior materials were tested in different reaction-to-fire tests. This was done in order to get the basic material properties regarding fire safety which enables estimation about the state of the art and also delivered material input data for numerical fire simulations. In the next step fire tests with single interior components as well as fire experiments in vehicle compartment were performed to assess typical fire scenarios in motor vehicles. These also serve well to establish comparative fire scenarios for applying in numerical fire simulations. With material input data gained several bus models were prepared for numerical fire simulations in which different fire scenarios being typical for motor vehicles were conducted in extension of fire tests performed.

The structure of the dissertation at hand introduces the fundamentals and the state of the art of fire science and fire safety engineering first. Following all the fire tests and experiments performed in small- and real-scale as well as the numerical fire simulations run are presented. Finally a summary and recommendation for further research can be gathered from a wrap-up at the end.

# 2. Fundamentals and State of the Art

This chapter provides a brief overview of the state of the art regarding fire science and of current fire safety engineering methods as well as the intersection shared by motor vehicles basics and the work at hand.

## 2.1 Fire Science and Fire Safety Engineering

In fire science the combustion and its effects as well as its behaviour and development are the key issues usually focused at. Predominantly investigation activities are undertaken to prevent unwanted fires and to enhance fire safety.

In order to provide a basic understanding for the dissertation at hand, the fundamentals of fire science are presented here. Also combustion relevant terms and processes are described in details.

### 2.1.1 Combustion and its Characteristics

To give a brief overview of what is meant by combustion and what happens within this process, the combustion and its characteristics are explained step by step.

Combustion is defined as an exothermic chemical reaction of substances with an oxidiser and thus is a redox reaction. Basically the combustion process is the oxidation of a fuel in presence of oxygen molecules with emission of heat and light. The fuel is the reducing agent and consists of combustible substances which usually include organic compounds. During a combustion process fire gases are released. Also flames and glowing are typical for combustions. In strict chemical sense oxidation means the loss of electrons. The fuel loses electrons while the oxygen gains them. This transfer of electrons releases heat and nearly always light. A combustion or more precisely an oxidation reaction can only occur if a reducing agent (fuel) and an oxidising agent (usually oxygen contained in the air) are present at once and if there is enough energy (e.g. heat) acting. Furthermore the chemical reaction between fuel and oxygen molecules entails the release of energy (mainly in form of heat) which stimulates further chemical reactions between fuel and oxygen molecules. All these processes initiate a chemical chain reaction which sustains the combustion process. [Compare with definitions in 1]

The combustion triangle as shown in Figure 1 is a simplified model to illustrate the fundamental components of a fire. The side edges which constitute the key elements of combustion are defined as fuel, oxygen and heat. Removing any of these three elements will prevent or extinct the combustion immediately. In Figure 1 the basic combustion triangle is extended by applicable examples for fundamental components participating.

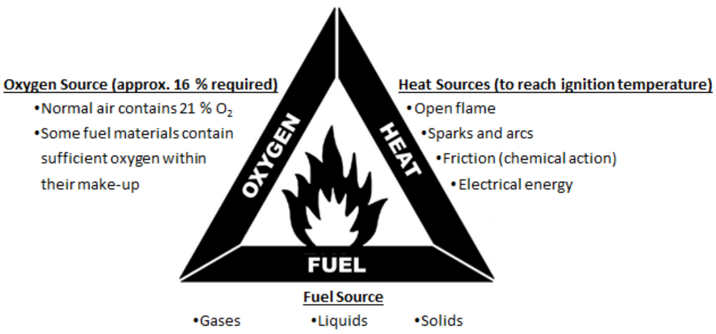



Figure 1 – Combustion Triangle [2]

Another model describing the major principle of combustions is given by the combustion tetrahedron. In contrast to the combustion triangle in the combustion tetrahedron the main elements are defined as triangular surfaces and the chain reaction (uninhibited) is supplemented as a fourth fundamental element as shown in Figure 2. The uninhibited chain reaction is a necessary process for continuing the combustion process. The molecules in reducing and oxidizing agents collide and release energy which sustains the combustion process.

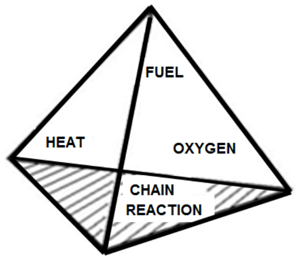



Figure 2 – Combustion Tetrahedron [3]

Technical terms of fire science are defined in DIN EN ISO 13943 [1]. Annex I contains the main combustion-relevant terms related to this work.

Generally fires can be divided into three combustion phases. First the fire starts in the fire initiation phase followed up by the fire developing phase and then by the fully developed fire phase [Compare with 4].

In microscopic view the initial combustion process on a material surface can be divided into three stages chronologically ordered. First the incipient stage is the preheating phase containing energy heating up the material surface. By doing so, combustible gases are released out of the material surface by a slow pyrolysis. Next phase, the smouldering stage, describes a fully developed and continuing pyrolysis process including ignition and the initial stage of combustion. Aerosol and smoke particles produce the visible part of the smouldering. Finally the flaming stage is the phase in which flames occur and the combustion increases to a fire. [Compare with 4]

As soon as the ignition is succeeded the combustion process occurs in two different modes, in the flaming and/ or in the non-flaming mode. The latter consists of smouldering or embers. Smouldering is a slow combustion process at relatively low temperatures. For the flaming mode fuel must be vaporised. In combustion processes with solid or liquid fuels the thermal impact causes burnable vapours getting released on the material surface. This effect is defined as pyrolysis. In solids the fuel vapours emerge by decomposition while in liquids they arise by evaporation. The burning of vapours generates the flames in the flaming mode and heats the fuel surface. This entails more burnable gases getting released and the combustion process continues or even increases. Both, the flaming and the non-flaming modes may occur separately or in combination. [Compare with definitions in 1]

Another combustion characteristic is marked by the mixture of fuel and oxygen which can principally occur in two different forms during the flaming mode. In one of them the gaseous fuel and oxygen are mixed prior to ignition (e.g. in Bunsen burners). This is defined as a premixed flame. Turbulence in the fluid dynamic of a flame can support the mixing process of fuel and oxidant as for instance applied in combustion engines. In the other case the fuel gases and oxygen are initially separate and the combustion takes place where both gases come together. That flame type is defined as diffusion flame and occurs mostly in unwanted fires. [Compare with 5]

Combustible materials can be classified by several aspects and can be basically characterised by its aggregate phase. Another way is given by EN 2 [6] which relates to the fuel involved to corresponding fire classes as shown in Table 1. The classification of fuel according to EN 2 [6] is predominantly introduced for an easy selection of extinguishing agents.

In addition to the current EN 2 classification a further electrical equipment class (Class E) for low voltage (< 1000 V) was part in the previous version. Class E was removed since the power supply has to be turned off in case of fire and since all available extinguishers are applicable to electrical fires (low voltage) by considering the safety distance printed on the extinguisher. So they would fall into any of the five categories of the EN 2 remaining.

Table 1 – European Fire Classes according to EN 2 [Compare with 6]

| European Fire Classes according to EN 2 | |
|---|---|
| Class A | Solid combustible materials that are not metals (e.g. wood, paper, plastics) |
| Class B | Flammable liquids (e.g. gasoline, oil and any non-metals in a liquid state) |
| Class C | Flammable gases |
| Class D | Metalls (e.g. potassium, sodium, aluminium, magnesium) |
| Class F | Cooking oil or fat |

The fire classes according to the EN 2 do not conform to the categories required in other regions of the world. Internationally there are different methods to allocate fuel in fire classes [7]. In Table 2 the European fire classes are compared with the American and the Australasian classification.

Table 2 – Fire Classes of Different Regions in the World [7]

| Fire Classes of Different Regions in the World | | | |
|---|---|---|---|
| **Fuel** | **European** | **American** | **Australasian** |
| Solid combustible materials | Class A | Class A | Class A |
| Flammable liquids | Class B | Class B | Class B |
| Flammable gases | Class C | Class B | Class C |
| Electrical equipment | - | Class C | Class E |
| Combustible materials | Class D | Class D | Class D |
| Cooking oil or fat | Class F | Class K | Class F |

A specific fire topic describing fires in enclosed rooms is given by compartment fires. The progress of a fire in a compartment is usually characterised by its heat release rate (HRR) profile. Figure 3 shows a HRR profile including the stages of a fire in a compartment and features also another approach describing a compartment fire by the temperature as ordinate. The temperature profile is usually used for calculations and standard tests which are based on temperature-time-curves. Principally both types of curves and their corresponding stages are comparable in shape as shown in Figure 3. [Compare with 8]

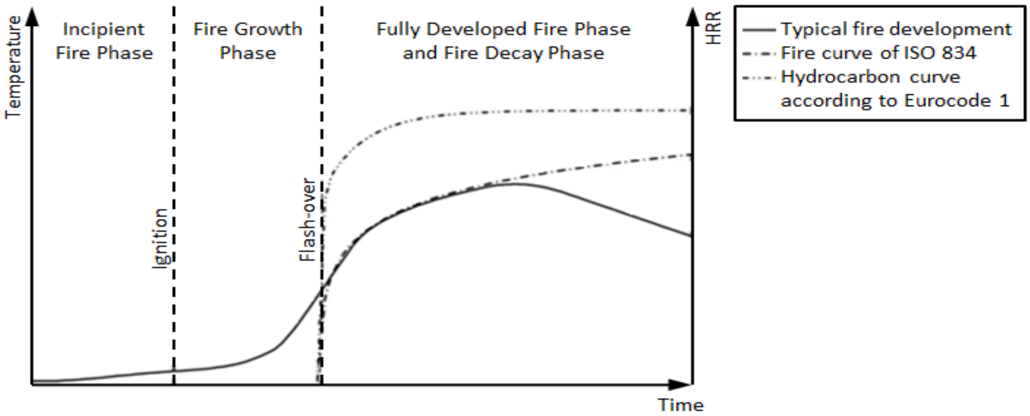



Figure 3 – Typical Temperature/ HRR Curve of Compartment Fires [compare with 8]

Compartment fires do not always match perfectly to the idealised fire development since the amount and kind of combustible material, available oxygen and ventilation profile around affect the fire development. For instance the peak temperature, the peak heat release rate or the burning duration may differ from the ideal profile.

The first stage, called incipient fire phase, defines the beginning period starting when combustible substances and oxygen are sufficiently available until the ignition process in which enough ignition power acts. This time period can differ widely, depending for instance on the ignition source and the combustible substances. [Compare with 9]

The second stage, called fire growth phase, begins immediately after ignition and characterises the time period in which further material nearby the ignition heats up and starts burning. The fire grows continuously while the average temperature of the room will increase slowly at this stage. [Compare with 9]

The third stage, called flash-over phase, describes the typical characteristic of a flash-over in which the state of total surface involvement of combustible materials (see definition of flash-over in [1]) is reached exceedingly fast. The combustion processes will greatly accelerate and will cause the fire to spread enormously in accordance with a rapid temperature increase and massive heat release. [Compare with 9]

The fourth stage, called fully developed fire phase, is marked by a compartment burning completely. Especially under the ceiling the temperatures are reaching a very high level which can be considerably higher than the decomposition temperatures of most materials containing major fire load. In this stage the fire is absolutely destructive and continues while the fire is supported by air needed for. [Compare with 9]

The fifth stage, called fire decay phase, describes the period of time in which the fire decreases due to an interrupted or exhausted supply of combustible material or oxygen. In this stage the average temperature of the compartment declines and converges slowly towards ambient temperature which at this point in time will be higher than prior the fire (as a result of the thermal conditions during the fire). [Compare with 9]

### 2.1.2 Fire Behaviour of Plastic Materials

Plastic materials are mainly organic high polymers consisting of large chainlike molecules containing carbon. Most interior parts for road vehicles are made of plastic materials usually consisting of polypropylene (PP), polyamide (PA), polyurethane (PU) and polyethylene (PE). Table 3 shows the typical plastic materials used in road vehicles and their scopes of application. [Compare with 10]

Table 3 – Plastic Materials of Interior Parts in Road Vehicles [Compare with 10]

| Typical Plastic Materials of Interior Parts in Road Vehicles | |
|---|---|
| **Plastics** | **Scope of application** |
| Polyurethane foam (PUR) | Dashboard, side panel, consoles, steering wheel, seats, insulation |
| Acrylonitrile butadiene styrene (ABS) | Dashboard, door and side panel, console |
| Polyvinyl chloride (PVC) | Inner lining, console, cable insulation |
| Polyamide (PA) | Inner lining seat cover, doormat |
| Polyester (PES) | Inner lining, seat cover, doormat |
| Artificial leather | Door and side panel, seat cover |

In the incipient stage of a combustion with plastics the surface layer of the plastic material heats up caused by heat radiation, convection or conduction from a heat source. As a result of this a thermal decomposition starts in the material surface layer entailed by an incipiently slow pyrolysis. In the following smouldering stage, in which aerosol and smoke particles generate the smouldering, this process develops to a fully developed pyrolysis. When enough ignition power acts in this phase, the combustible gases start to react with oxygen molecules and initiate the combustion. Additionally the heat generated in the redox reaction of the oxidation process supports the decomposition in the next layer of the plastic material. Further combustible gases are released and sustain the combustion process. The plastic material ignites and the combustion changes into the flaming stage and lastly the combustion increases to a fully developed fire. [Compare with 9]

In Figure 4 the physical and chemical processes on and in the surface layer of plastic materials during a combustion process are generally shown. Although all four process sections will pass off more or less simultaneously, they have to be described one after the other. The first section describes the different aggregate state areas in the surface layer. The second section shows the processes influencing the heat transport within the surface layer. In the third section the thermal interaction in the surface layer is explained. In the fourth section the flame regions and the material flow from solid polymer to gaseous combustion gases are described. Finally the area of pyrolysis is shown in the fifth section.

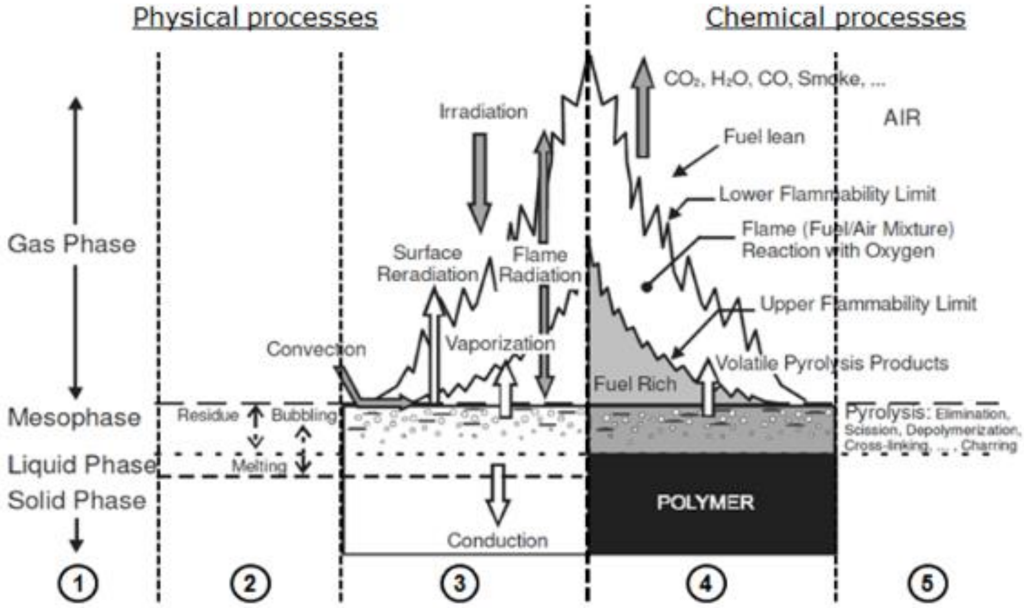



Figure 4 – Processes in Surface Layer of Plastic Materials while Combustion [11 complemented]

Plastic materials can contain additives for fire and/ or flame resistance. Particularly a fire retardant is a 'substance added, or a treatment applied, to a material in order to delay ignition or to reduce the rate of combustion'. In contrast a flame retardant is a 'substance added, or a treatment applied, to a material in order to suppress or delay the appearance of a flame and/ or reduce its propagation'. [Compare with definitions in 1]

Smoke gases are one of the main combustion products. Especially plastic materials burning generate high amounts of smoke which can be extremely hazardous. Toxic smoke gas substances are difficult to perceive and are hard to cope with for humans. The quantitatively most common combustion product gas of plastic materials and principally of all organic materials is carbon dioxide ($CO_2$). Extremely toxic smoke gas components in lethal concentrations can also be the outcome of burning plastic materials. In Table 4 typical plastic materials used in road vehicles are summarised including their typical main smoke gas components.

Table 4 – Interior Parts and their Main Combustion Gases [Compare with 10]

| Interior Plastic Parts of Road Vehicle and their Main Combustion Gases | |
|---|---|
| **Plastics** | **Combustion gases** |
| Polyurethane foam (PUR foam) | CO, $CO_2$, HCN, $NH_3$ |
| Acrylonitrile butadiene styrene (ABS) | CO, $CO_2$, HCN |
| Polyvinyl chloride (PVC) | CO, $CO_2$, HCl |
| Polyamide (PA) | CO, $CO_2$, tar, HCN |
| Polyester (PES) | CO, $CO_2$, HCN, acetaldehyde |
| Artificial leather | CO, $CO_2$, HCl, HCN, $NH_3$ |

Under ideal combustion conditions (complete combustion) the carbon molecules react almost completely to carbon dioxide ($CO_2$) and water vapour. However, the combustion products contain also carbon monoxide (CO) as well as other toxic smoke gas components such as nitrous gases ($NO_x$), hydrogen bromide (HBr), hydrogen chloride (HCl), hydrogen cyanide (HCN), hydrogen fluoride (HF) and sulphur dioxide ($SO_2$) depending on the kind of polymer burnt. These toxic smoke gas components are caused by organic molecules which are commonly derived from petrochemicals.

### 2.1.3 Engineering Methods in Fire Safety

Predominantly fire safety engineering focuses on buildings and industrial facilities. However, electronic equipment, furniture, textiles and transport means are also focus areas. In sum fire safety engineering has a wide range of topics which are simply summarised as fire safety and which all are met by engineering. According to DIN EN ISO 13943 fire safety engineering is defined as 'application of engineering methods based on scientific principles to the development or assessment of designs in the built environment through the analysis of specific fire scenarios or through the quantification of risk for a group of fire scenarios' [1]. A more general definition which does not focus on civil engineering only would read: Fire safety engineering is the application of fire science with engineering principles to protect people and their environments from the effects of fire and smoke.

Key issues of fire safety engineering are precautions preventing fires and mitigating consequences in case the fire prevention measures failed. Precautions preventing fires mean basically the inhibition of ignitions and fire spreading. Related to the typical progress of a compartment fire as shown in Figure 4 the fire safety precautions are primarily focused on fire inhibition in the incipient fire phase and in the fire growth phase. An ignition can be prevented and a fire development interrupted if one or more elements of the fire triangle or fire tetrahedron are missing or removed as described in Chapter 2.1.1. Since sufficient oxygen is normally available in the air, combustible fuel and/ or ignition power should be primarily removed to avoid fire.

Precautions mitigating consequences of failed fire prevention measures comprise fire protection in the fully developed fire phase. Specific application areas are fire containment based on fire-resisting materials and/ or on fire barriers to prevent danger of life and resulting damage. Therefore an estimation of fire behaviour is absolutely essential.

Further fields of fire safety engineering are fire detection and fire extinguishing. Fire detection systems are predominantly needed to alarm persons who are endangered in case of fire. Fire detectors usually respond to smoke or heat, both of which are typical fire characteristics. Smoke detection is based on a photo-electric sensor and heat detection is initiated by mechanical movements closing an electrical circuit due to the action of heat. To extinguish a fire means to put it out by taking away one or more elements of the fire triangle or the fire tetrahedron. Most fire suppression methods are principally based on cooling processes (e.g. by water) and/ or on displacing oxygen (e.g. air). Another possible approach to extinguish fires would be to interrupt the chemical chain reaction, however this is rarely used. In sum several fire suppression agents are available. Picking out the most feasible one mainly depends on the materials involved and the temperature estimated. In principal the extinguishing agents can be gaseous, liquid or solid.

Best practice for enhancing fire safety is to perform real-scale fire tests iteratively for adjusting against and/ or to eliminate unwanted fire behaviour effects. But most applications of fire safety engineering are very complex and/ or thus too extensive to be reproduced fully in real-scale fire tests (e.g. fire in buildings or industrial facilities). However, fire tests which have been ’scaled down‘ do not produce reliable results, since the actual fire is not scalable. Therefore modelling fire can be expedient. Basically analytical and simulative approaches can be used. Figure 5 shows a pyramid imaging the universal validity and computational cost of fire modelling methods.

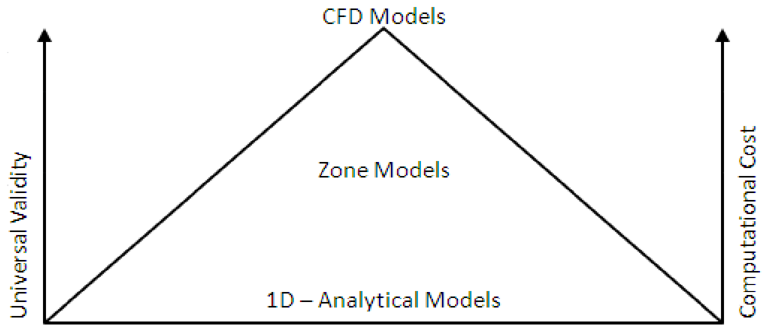



Figure 5 – Universal Validity and Computational Cost of Fire Model Methods [Compare with 12]

Analytical fire models are predominantly based on plume models which reflect a simplified mass and energy balance. This method is used to determine the temperature profile of fires by computing steady-state and in one dimension. But this is only applicable to a limited range of specific conditions. The equations used originate from empirical experiments and are not applicable to predict the chronological fire development. Since plume models cannot be transferred to complex fire scenarios they are not state of the art anymore.

Zone models are based on a method that separates the considered enclosure into zones of uniform conditions to calculate the temporal changes. Usually a two zone model is used which devides a room in an upper and a lower zone. The upper layer is then the hot smoke area, while the lower layer consists of cool air containing none smoke particles only. Assuming that the existent gases in each layer are mixed well, the smoke distribution in the upper layer is homogeneous and the lower layer contains air only. Therefore the conditions within each layer are constant over a time step. Mass and energy conservations are the fundamental equations. With a zone model for instance the temperatures of the upper and lower zone, the smoke layer height and its visibility as well as the time to fire alarm activation and time to flashover can be predicted. In addition openings to the outside or to other compartments simulating escape of smoke and heat can also be included. Typical model inputs are the enclosure dimensions, sizes and locations of openings, characteristics of implemented items and their heat release rates.

Field models are numerical fire simulations based on computational fluid dynamics (CFD) which have been grown to an essential tool in fire safety engineering in the last years. Especially since the computational power of computers has been enhanced enormously and since CFD software have been improved to comfortable programs the numerical fire simulation has become a fundamental method in fire safety engineering. Meanwhile CFD fire models can provide estimations of fire behaviour more accurately and faster than every method before. Measures for fire prevention and/ or fire control can be implemented in the fire simulations. Also the test procedure or set-up can simply be modified without needing to prepare a complete new scenario.

Generally CFD simulates the movement of heat and smoke within a given environment by solving conservation equations (e.g. for mass, momentum and enthalpy). Initial and boundary conditions can be easily factored in. For numerical steps of calculation the enclosure in a field model is split into a large number of cells. Depending on the simulation program the mesh can be either structured or unstructured. In structured meshes the cells are uniform cubes or hexahedrons. Conversely, more complex cell shapes such as non-uniform tetrahedrons or mixed shapes constitute unstructured meshes. In a field model for each period of time the transfer of mass, momentum and energy between adjacent cells will be calculated by applying the following general conservation equation as shown in equation (2.1) [12]. Therein, accumulation is defined by the term $\frac{\partial}{\partial t}(\rho\phi)$, convection by the term $\frac{\partial}{\partial x_i}(\rho\phi)$, diffusion by the term $\frac{\partial}{\partial t}\left(\Gamma_\phi \frac{\partial\phi}{\partial x_i}\right)$ and the source by the term Source $S_\phi$.

$$0 = \frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_i}(\rho\phi) - \frac{\partial}{\partial t}\left(\Gamma_\phi \frac{\partial\phi}{\partial x_i}\right) - S_\phi, \tag{2.1}$$
$$\phi = [1, u_i, h, c_k]$$

## 2.2 Fire Safety Aspects in Vehicle Engineering

Generally all road vehicles comply with the same basic fire safety standard. However, due to the high number of passengers and the very straitened escape conditions additional requirements must be applied to buses.

In order to provide a holistic consideration a brief overview of vehicle types is given, followed by looking at what defines a bus. Vehicle categories are basically defined by the third revision of ECE/TRANS/WP.29/78 [13]. Table 5 summarizes its main items for classification. In the following the category 'Motor Vehicles' are focused further only.

Table 5 – Categories of Vehicles [13]

| Categories of Vehicles | |
|---|---|
| Power-driven vehicle | Any self-propelled road vehicle, other than a moped in the territories of Contracting Parties which do not treat mopeds as motor cycles, and other than a rail-borne vehicle. |
| Motor vehicle | Any power-driven vehicle which is normally used for carrying persons or goods by road or for drawing, on the road, vehicles used for the carriage of persons or goods. This term embraces trolley-buses, that is to say, vehicles connected to an electric conductor and not rail-borne. It does not cover vehicles such as agricultural tractors, which are only incidentally used for carrying persons or goods by road or for drawing, on the road, vehicles used for the carriage of persons or goods. |
| Motor cycle | Any two-wheeled vehicle, with or without side-car, which is equipped with a propelling engine. Contracting Parties may also treat as motor cycles in their domestic legislation three-wheeled vehicles whose unladen mass does not exceed 400 kg. The term "motor cycle" does not include mopeds, although Contracting Parties may treat mopeds as motor cycles for the purpose of the Convention. |
| Moped | Any two-wheeled or three-wheeled vehicle which is fitted with an internal combustion engine having a cylinder capacity not exceeding 50 cm³ and a maximum design speed not exceeding 50 km per hour. |

| | |
|---|---|
| Trailer | Any non-self-propelled vehicle, which is designed and constructed to be towed by a power driven vehicle and includes semi–trailers. |
| Combination of vehicles | Coupled vehicles which travel on the road as a unit. |
| Articulated vehicle | A combination of vehicles comprising a motor vehicle and semi–trailer coupled to the motor vehicle. |
| Road tractor | Road motor vehicle designed, exclusively or primarily, to haul other road vehicles which are not power-driven (mainly semi–trailers). |
| Agricultural tractor | A vehicle specifically designed to deliver a high tractive effort at slow speeds, for the purposes of hauling a trailer or machinery. |

Vehicles used for carrying passengers are of interest for this work only. Those are classified in subcategories M1 to M3 according to ECE/TRANS/WP.29/78 [13] depending on their amount of passenger seats. M1 defines ’vehicles having no more than eight seats in addition to the driver seat‘ [13]. Both other contain ’Vehicles used for the carriage of passengers, comprising more than eight seats in addition to the driver's seat‘ [13]. But in detail M2 is limited to vehicles ’having a maximum mass not exceeding 5 tonnes‘ [13] while M3 contains vehicles ’having a maximum mass exceeding 5 tonnes‘ [13].

In accordance with ECE/TRANS/WP.29/78 M2 and M3, buses can further be divided into the subclasses Class I to Class III as well as into subclasses Class A or B as shown in Table 6. The dissertation at hand predominantly focuses on M3 buses which conform to at least one of the bus design classes shown in Table 7.

Table 6 – Subclasses of M2/ M3 according to ECE/TRANS/WP.29/78 [13]

| **Subclasses of M2/ M3 according to ECE/TRANS/WP.29/78** | |
|---|---|
| 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 |
| Class III | Vehicles constructed exclusively for the carriage of seated passengers |
| 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 |

Table 7 – Bus Design Categories according to ECE/TRANS/WP.29/78 [13]

| **Bus Design Categories according to ECE/TRANS/WP.29/78** | |
|---|---|
| Trolleybus | A bus of Classes I, II, or III, electrically driven by energy from external wires |
| Articulated bus | A bus which consists of two or more rigid sections which articulate relative to one another; the passenger compartments of each section intercommunicate so that passengers can move freely between them; the rigid sections are permanently connected so that they can only be separated by an operation involving facilities which are normally only found in a workshop |
| Low floor bus | A vehicle in which at least 35 per cent of the area available for standing passengers (or of its forward section in the case of articulated vehicles) forms a single area without steps, reached through at least one service door by a single step from the ground. |
| City bus | A bus of Class II |
| Coach | A bus of Class III |
| High decker | A bus of Class II and III which have steps between the doors and the passenger deck |
| Double decker | A bus of Class II and III which have a second passenger deck |

### 2.2.1 Status Quo of Research on Fire Safety of Road Vehicles

The amount of occurred fire incidents in road vehicles and especially in operating buses and coaches as well as the related number of injuries and fatalities have brought the fire safety of road vehicles into focus of research. This hasn't been observed in a specific region only, rather it is monitored globally as for instance reported for the USA [14,15], for Scandinavia [16,17] or for Germany [18] and France [19] with almost similar results. So, research was done for identifying and mitigating the related risks to improve the fire safety of road vehicles mainly driven in the USA [20, 21] and Sweden [22].

To get the status quo of how far modern methods were applied in fire safety of road vehicles a review was conducted. Due to a European TRANSFEU project numerical investigations were brought into the transportation sector [23]. These investigation were related to rail vehicles only while buses and other road vehicles were left untouched. Furthermore, numerical investigations were set up on raw material properties only and haven't been verified by separate fire tests in this project. Regarding fire safety of buses, research was initiated by the SP Technical Research Institute of Sweden (RISE today) once they tested bus interior materials and found out that there is a need for enhancing the fire safety. As a result of this, SP started a bus fire project wherein a couple of fire tests with material typical for bus interiors were conducted and also some numerical fire simulations were run to estimate the fire development within a bus fire [22]. However, the calculation performance of computer and also the used simulation software were not on the status as today and thus the results have been qualitatively limited. Beside of this, the dissertation at hand comprise an approach combining material tests, real-scale fire test and numerical simulations in a manner hasn't been done before.

### 2.2.2 Fire Safety Requirements for Road Vehicles

Generally fire safety requirements of road vehicles focus on parts containing fuel and on a fire test for interior materials. The reaction-to-fire test specification required is globally applied and shall be conducted everywhere in the same manner. The objective of this test is to limit the horizontal burning rate. A specimen dimensioned 356 mm x 100 mm x thickness is mounted in an U-shaped specimen holder as shown in Figure 6 on the left which is placed horizontally in a combustion chamber as shown in Figure 6 on the right. During testing a 38 mm low-energy flame of a Bunsen burner is pointed to the free front end of the material sample and will be flamed for 15 s. The time needed to pass the distance between the first and third measuring point, which amounts 254 mm, is required to establish the horizontal burning rate. For passing the test the horizontal burning rate of the material shall be equal or less than 100 mm/min. [24]

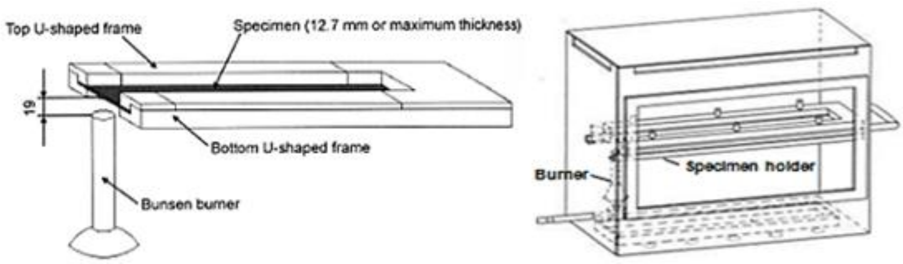



Figure 6 – Test Specimen and Test Rig of Horizontal Fire Test According to FMVSS 302 [24]

Test method of the horizontal fire test originates from the American FMVSS 302 [24] standard and was developed in the 1960s to reduce the fire hazard in road vehicles due to cigarettes and lighters. Table 8 shows a selection of international standards and manufacturer's specifications using this fire test.

Table 8 – Fire Safety Standards for Road Vehicles based on FMVSS 302

| Fire Safety Standards for Road Vehicles based on FMVSS 302 | |
|---|---|
| **International Standards** | **Manufacturer's specification** |
| ISO 3795 (Int.) | GS 97038 (BMW) |
| 95/28/EC (EU) | DBL 5307 (Daimler) |
| DIN 75200 (D) | FLTM-BN 24-2 (Ford) |
| FMVSS 302 (USA) | GM 6090 M (GM) |
| U.T.A.C. 18-502/1 (F) | MES DF 050D (Mazda) |
| BS AU 169 (GB) | ES–X60410 (Mitsubishi) |
| JIS D 1201 (J) | PTL 8501 (Porsche) |
| | D45 1333; (Renault) |
| | STD 5031,1 (Volvo) |
| | TL 1010 (VW) |

Fire safety requirements for buses are principally harmonized for almost all countries around the world by UNECE (United Nations and their Economic Commission for Europe). They are also part in the EU directives. In detail the EU directive 95/28/EC [25] contains the 'burning behaviour of materials used in the interior construction of certain categories of motor vehicle' which conforms to the ECE Regulation No. 118 managing the 'uniform technical prescriptions concerning the burning behaviour and/ or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles' [26]. This directive stipulates specific fire tests which bus interior materials need to undergo, such as the 'test to determine the horizontal burning rate' [Appendix VI of 26] required for all road vehicles. In addition the ceiling and parts bordered need also to pass a 'test to determine the melting behaviour of materials' [Appendix VII of 26]. Bus interior parts mounted in vertical direction need to fulfil a 'test to determine the vertical burning rate of materials' [Appendix VIII of 26]. The vertical burning rate shall not exceed 100 mm/min. Insulation materials installed in engine compartments need to undergo a test to establish sufficient repelling fuel and lubricant behaviour [Appendix IX of 26]. This is an additional requirement for buses because in many cases insulation materials soaked with burnable liquids have been reason for engine compartment fires. Also for electrical cables flame propagation requirements have been enhanced on level ISO 6722, paragraph 12 [Appendix VIII 26].

'In Germany safety of road vehicles is basically regulated by the German Road Traffic Licensing Regulation (StVZO [27]) in which also legal requirements of European directives are implemented. Generally §30 StVZO demands a vehicle construction and equipment for a maximal passenger safety, especially in case of a traffic accident. §30d StVZO specifies the requirements for buses and is complemented by the annexes I to VI, VIII and IX of EU directive 2001/85/EC [28] which is often referred to as 'bus directive' and conforms to UNECE Regulation No. 107 [29]. Regarding the fire safety of buses §35g StVZO demands fire extinguishers, §45 StVZO defines the requirements for fuel tanks and §46 StVZO regulates the requirements for fuel lines [27] as required in UNECE Regulation No. 36 [30] as well. Concerning the reaction-to-fire behaviour of bus interior materials §35j StVZO rules the requirements which are complemented by the appendixes IV to VI of EU directive 95/28/EC' [25]. In Annex II the fire safety regulations for buses in Germany are summarized.

To compare the fire safety performance between road vehicles and other transport means Table 9 summarises fire tests required for respective interior materials. This table also shows that most reaction-to-fire tests are required for materials of all transport means but not for buses interior materials. For instance quantifying the heat release rate with a Cone Calorimeter (ISO 5660-1 [31]) or analysing smoke production and toxicity with an FTIR (Fourier-transform Infrared Spectroscopy) connected to the Smoke Density Chamber (ISO 5659-2 [32]) as well as extra fire tests for passenger seats are not required for materials applied in buses only. Thus, the interior materials of buses only need to comply with the lowest fire safety requirements compared with all other transport sectors.

Table 9 – Fire Tests for Interior Materials in Different Transport Means [Compare with 33]

| Fire Tests for Interior Materials in different Transport Means | | | | |
|---|---|---|---|---|
| | **Buses (ECE R 118 [26])** | **Rail vehicles (EN 45545-2 [34])** | **Ships (SOLAS Chapter II-2 [35])** | **Aircrafts (FAR 25.853 [36]/ JAR 25.853 [37])** |
| Horizontal burning rate | ISO 3795 (horizontal mounted components) | No test | No test | FAR/ JAR/ CS 25.853 b(5) (cabin and cargo compartment) |
| Vertical burning rate | ISO 3795 (vertical 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) |
| Heat release rate | No test | ISO 5660-1 (most materials) | ISO 5660-1 (fire-restricting materials in high speed crafts) | FAR/JAR/CS 25.853(d) (cabin compartment) |
| Smoke density | 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 | ISO 5659-2 (most materials) | ISO 5659-2 (most materials) | BSS 7239/ ABD 0031 (cabin compartment) |
| Calorimeter test for seats | No test | ISO 9705-2 (passenger seats) | ISO 8191-1/-2 (upholstered furniture) | FAR/JAR/CS 25.853(c) (upholstered furniture) |

### 2.2.3 Fire Safety Items affected by Motor Vehicle Design

Due to the variety of road vehicle types and its individual design characteristics covering all types of motor vehicles would be too extensive. Since the focus of the dissertation at hand lays on buses the basic structure and the modular design of road vehicle is predominantly referred to them.

Regardless of the bus type, for instance a double decker, a high decker or a city bus, the fundamental chassis and the base frame are made from steel as shown in Figure 7. The body of buses consists completely of metal sheets and window panels. In newer buses sometimes plastic panels are partly used instead of steel sheets. The flooring usually consists of plywood boards coated with rubber on the top surface. The other bus interior parts are mainly made up of plastic components.

Figure 7 – Typical Base Frame of Buses [38]

The inner shape of all buses is usually a simple cuboid which is segmented into compartments. In all types of buses the biggest compartment is the passenger cabin which shall provide place for as many passengers as possible. Also the engine compartment is commonly located in the back, while the driver's cockpit is always placed at the bus front behind the windscreen.

Typically city buses do not consist of more than these three main compartments. Even the passenger cabin of a double decker consists more or less of only one compartment which is split into upper and lower deck. Figure 8 shows two types of single-deck buses, which just differ regarding their length of the passenger cabin and in mechanical aspects, such as an additional axle and an articulation system. In some few cases also double decker buses are used for the urban passenger transportation.

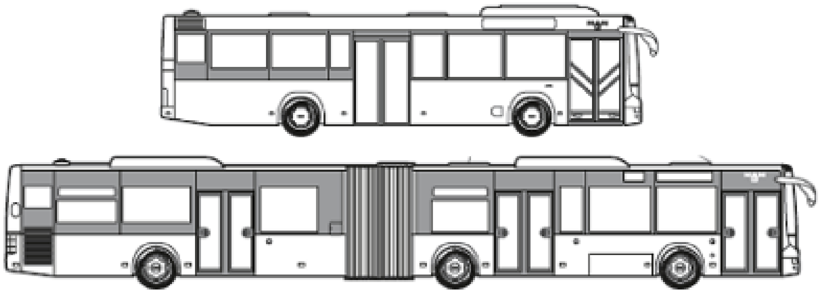


Figure 8 – Typical Construction Design of City Buses [39]

The interior of city buses are more or less similar. The doors are always orientated towards the footpath which is, depending on the driving direction of the particular country, on the right or on the left side. The front door is close to the driver. The second door is located in the middle of the vehicle with an adjacent area for pushchairs or wheelchairs as shown in Figure 9. Double decker buses features two interior staircases to reach the second passenger deck. In passenger compartments the passenger seats are serially positioned in longitudinal direction as shown in Figure 9. Only in exceptional cases the seats are installed in cross direction. The gangways and the areas allocated for pushchairs and wheelchairs can be used for standing passengers as well.

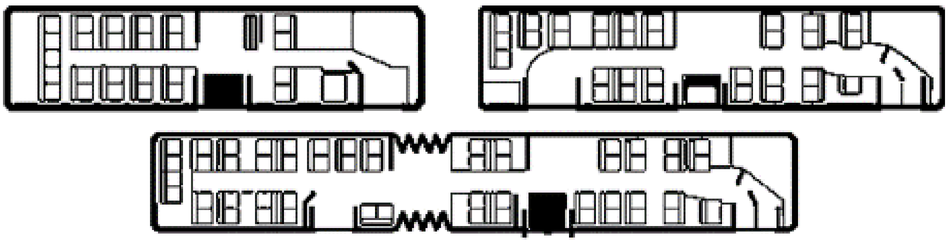


Figure 9 – Typical Room Layouts of City Buses [40]

The typical design of coaches is predominantly the high decker as drafted in Figure 10 on the left, whereas double deckers are rarer as sketched in Figure 10 on the right.

Figure 10 – Typical Designs of Coaches [38, 39]

In contrast to city buses the coaches contain additional compartments for luggage as drafted in Figure 11 on the left and often feature a galley as visible in Figure 11 in the middle and/ or a lavatory as shown in Figure 11 on the right. In coaches a driver's sleeping room is usually adopted as shown in Figure 12 as well. However, it is only allowed to be used while the bus is at halt. Sleeping compartments for bus passengers are not permitted any longer since every passenger must be strapped while driving.

Figure 11 – Typical Luggage Compartment, Galley and Lavatory in Coaches [38]

Figure 12 – Location of Driver's Sleeping Room in High Deckers and in Double Deckers [38]

The room layout of coaches is even more uniform than the one of city buses and has only two smaller doors orientated to the footpath. The first door is close to the driver but on a low level. The passenger cabin in high deckers can only be accessed via stairs adjacent to the doors. In double decker the bottom deck is generally on the driver's level too. Two stairs for reaching the second deck are positioned close to the doors. The passenger seats in coaches are throughout arranged serially as sketched in Figure 13. Some coaches are additionally equipped with a lavatory which usually is located in the lower deck nearby the second door. If high decker has a galley as well, it is mostly located on top of the lavatory. In double decker both are often directly side by side.

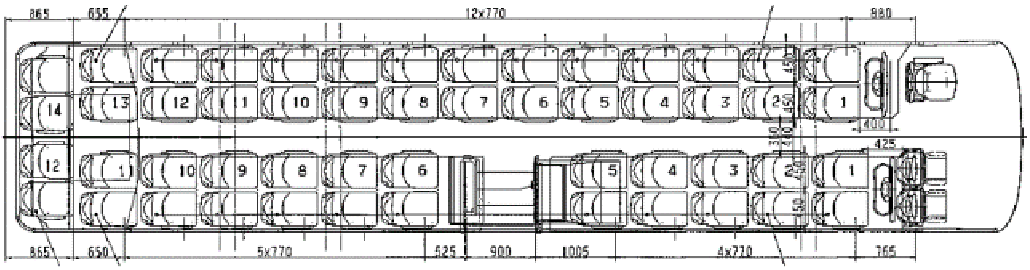


Figure 13 – Typical Room Layouts of High Decker Coaches [41]

Regarding fire development in a bus the ventilation is a main issue. Principally the ventilation concepts for buses are widely similar. Fresh air, regardless of whether warmed or cooled, is let in above passenger seats as indicated by colourful air jets above passenger seats in Figure 14 whereby the air pressure in the passenger cabin is minimally increased. In city buses the outflow of the air is caused by the overpressure in the passenger cabin and takes place at leaking doors and trap windows. In coaches which usually drive faster than city buses, the doors and windows are tight. Therefore, in the ventilation concept of a coach the air streams due to the overpressure in the passenger cabin through openings alongside the bottom of the gangway into the luggage compartment. While driving a bottom opening in the front of the underfloor induces a local negative pressure which causes the air to stream through the luggage compartment and to leave the vehicle at this opening. Figure 14 shows a snapshot of a CFD simulation with a bus at halt on the left and a bus driving at 80 km/h for comparison on the right. In both simulations the doors and windows are closed and the air inlet nozzles have similar predefined flow rates of 0.5 m/s. In the picture on the left the typical air flow is not entailed by the bus since the bus is standing wherefore the negative air pressure in the underfloor is not generated. In comparison, the complete chain of air flows while driving, starting from inlet nozzles, going through openings from the passenger cabin into the luggage compartment and finally leaving the bus in the front of underfloor, is shown in the picture on right.

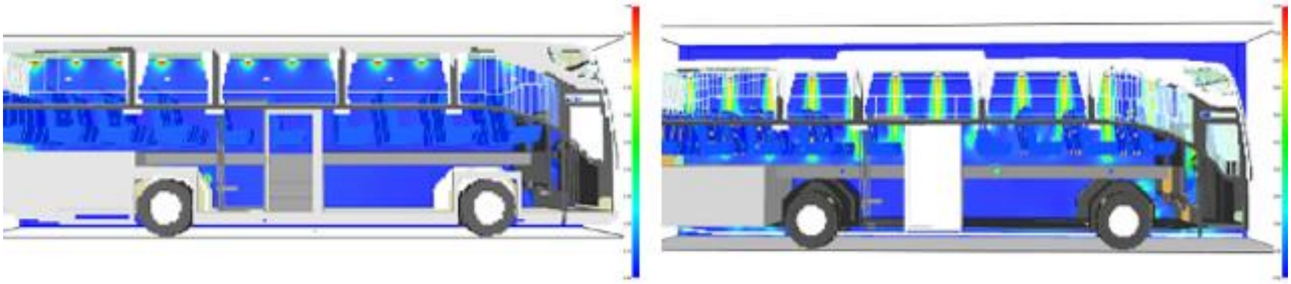


Figure 14 – Ventilation simulated in a standing coach (left) and in a driving coach (right)

### 2.2.4 Fire Detection Systems for Motor Vehicles

Most bus fires start in engine compartments [33] which commonly comprise 4 to 6 m³ densely equipped with many different sorts of components. A strong airstream is predominantly needed for cooling the diesel engine and the turbocharger. The latter can reach operating temperatures of up to 1000 °C and might become a fire source if getting contact to even small amounts of fuel or lubricant. This is why fire detection systems have become mandatory for bus engine compartments. Since also a lot of fires start unnoticed in other bus compartments, often entailed by an electrical defect or an overheating, fire detection is also stipulated for all hidden compartments. Generally fire detection systems alert the bus driver about the event of fire. Detectors in engine compartments are often connected to a fire suppression system.

However, each bus compartment is subjected to a different operational environment (e.g. engine or luggage compartment). Therefore several fire detectors for road vehicles are available on the market and have been investigated. On one side they can be split into spot or linear sensing detection. Spot detectors observe their directly surrounding environment only while linear detectors monitor the area along the longitudinal direction they are installed in. On the other side these fire detectors can be distinguished in regard of their detection approach which monitors combustion properties, such as typically the heat, smoke density or optical flaming. Detectors investigated for application in engine compartments are summarised and shown in Figure 15.

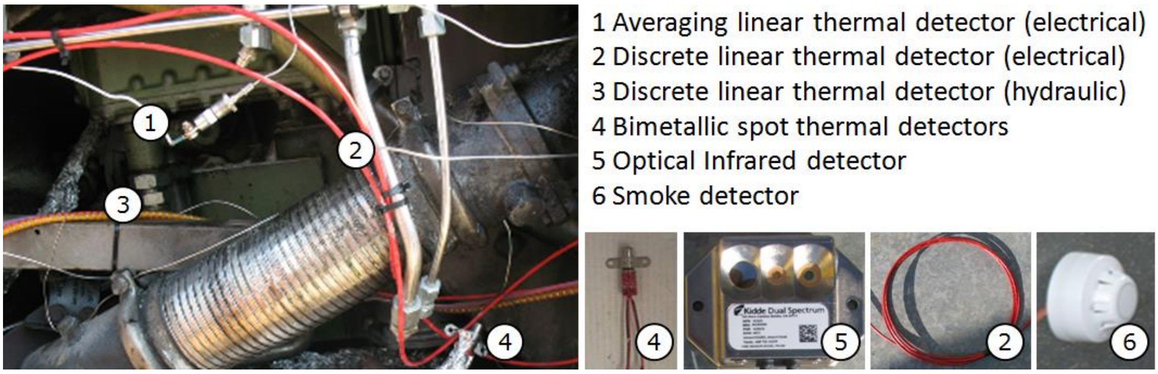



Figure 15 – Fire Detectors applied in Engine Compartment Fire Tests

Bimetallic spot thermal detectors are current switches designed to close an electrical short circuit for triggering alarm using the bimetallic deflection effect [compare with 42]. When surrounding air exceeds a temperature of 177 °C/ 350 °F the bimetallic thermal detector causes a short circuit fault.

Smoke detectors apply the photoelectrical principle of smoke particles interference. A transmitter sends out an infrared light beam and a receiver measures how much arrive from there. In case the transmission is interrupted or a transmission threshold is undercut the smoke detector triggers alarm [compare with 42]. Principally smoke detectors are unsuited for application in dirty areas such as engine compartments, since dirt (e.g. dust, fuel lubricant) would interrupt the light transmission and would entail false alarm.

Optical detectors are more or less flame sensors which respond to the waves of radiant energy emitted by a flame and operate in a specific spectrum ranging in either the visible IR or UV spectrum [compare with 42].

Linear thermal detectors can be compared with flexible wires detecting fires at any point along their length and can have a length long enough to observe the complete space. In detail discrete linear thermal detectors triggers as soon as the temperature exceeds the alarm threshold anywhere along its length. Hydraulic ones are a tube filled with a liquid under pressure. In case affected by fire the tube starts to leak and thus the pressure in it decreases which activates fire alarm [compare with 42]. Electrical ones consist of two cable wires separated by a thin temperature-sensitive insulation. When exceeding the temperature level the insulation between the two cable wires is melting and thus causing an electrical short which triggers a fire alarm signal [compare with 42].

In contrast to discrete linear thermal detectors the averaging ones work electrically only and triggers alarm in case the average temperature along the detection length exceeds a pre-set value [compare with 42].

# 3. Experiments

Experiments were run to evaluate fire safety performance of buses. Several bus interior materials were examined in small-scale and single parts up to a real bus were investigated in real-scale.

## 3.1 Experiments in Small-scale

Fire tests in small-scale were performed to obtain material data for assessing the fire safety performance of bus interior materials and to get input data for numerical fire simulations. Results gained in these tests allow comparing the reaction-to-fire behaviour of the materials applied in buses with those complying with requirements of other transport means, such as trains, ships and airplanes. In Table 10 the materials examined in small-scale tests are summarised.

Table 10 – Samples from Bus Interior examined in Small-scale Tests

| Samples from Bus Interior examined in Small-scale Tests | |
|---|---|
| Ceiling I | Sample of the ceiling located over passenger seats |
| Ceiling II | Sample of the ceiling located in the aisle |
| Dashboard | Sample of the cockpit |
| Flooring | Sample of the flooring in the passenger compartment and from the luggage compartment as well |
| Floor covering | Sample of the flooring in the aisle |
| GRP part | Sample of the glass reinforced plastic applied in the interior panelling for stairs, flaps and lavatories |
| Insulation | Sample of the insulation of the body (between the steel frame) |
| Seat foam | Sample of the foam used for the seat upholstery |
| Side panel | Sample of the cover towards the steel frame and the insulation material |

### 3.1.1 ATR Spectroscopy

The ATR spectroscopy is a practice of Mid-Infrared (IR) spectroscopy which is a very reliable and well recognized method for determining material compositions. Substances can be characterized, identified or also quantified by comparing material data in a deposited database. One of the strengths of IR spectroscopy is its ability as an analytical technique to obtain spectra from a very wide range of solids, liquids and gases [compare with 43]. In Figure 16 the correlation of the dashboard material against the best suiting material reference is shown as an example for an almost congruent material correlation. Curves of all other materials tested are attached in Annex III.

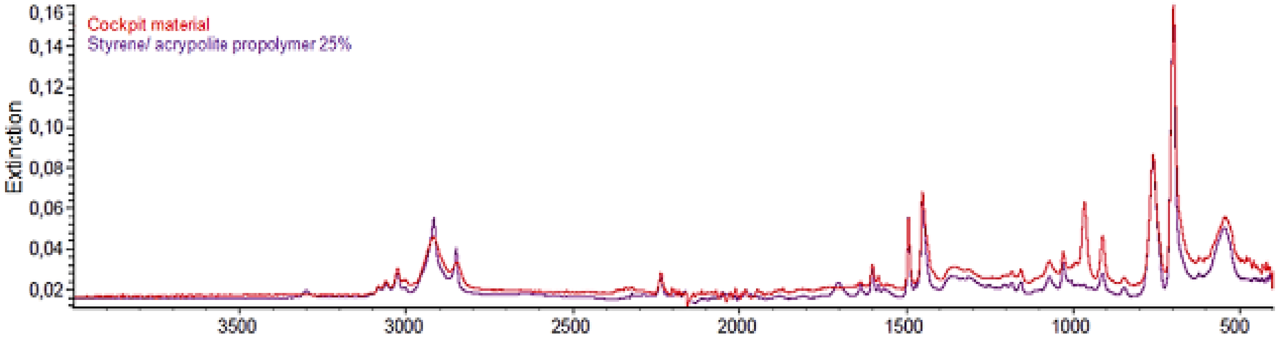



Figure 16 – ATR Curves Correlation of Dashboard Material and best suiting Material Reference

Table 11 shows the main ingredients of materials identified with the ATR spectroscopy method and their excellence of correlation.

Table 11 – Main Ingredients of Interior Materials identified with the ATR Spectroscopy Method

| **Main Ingredients of Bus Interior Materials identified with the ATR Spectroscopy Method** | | | |
|---|---|---|---|
| **Sample** | **Main material composition** | **Excellence** | **Remark** |
| Ceiling I | Polyether urethane, polypropylene oxide and methylene | 70,79 % | White sample |
| | Acrylic polymer | 78,55 % | Grey sample |
| Ceiling II | Undefined | no correlation | Green sample |
| | Poly (vinyl acetat:ethylene) 3:1 | 73,18 % | Grey sample |
| Dashboard | Styrene/ acrypolite propolymer 25% | 93,78 % | |
| Flooring | Undefined | no correlation | Plywood |
| Floor covering | Isodecyl diphenyl phosphate | 72,19 % | |
| GRP part | Styrene/ butyl methacrylate (50%) copolymer | 68,08 % | Indoor flap |
| Insulation | Melamine-formaldehyde condensate | 79,58 % | Foam |
| Seat foam | Polyether urethane, PPO+ MBI, pyrol. | 79,21 % | |
| Side panel | Undefined | no correlation | |

### 3.1.2 Cone Calorimeter

The Cone Calorimeter is one of the fundamental measuring instruments for quantitative analysis in the materials flammability research. This apparatus contains a uniform and well-characterized conical heat irradiance source as shown in Figure 17. Investigation parameters are heat release rate (HRR), time to ignition (TTI), total heat release (THR) and mass loss rate (MLR). The measurements of the HRR can be used to calculate the average rate of heat emission (ARHE), the maximum of the average rate of heat emission (MARHE) and the time to reach the maximum heat release rate. The Cone Calorimeter can also measure the smoke production and the ratio of $CO/CO_2$ [compare with 44 and 45].

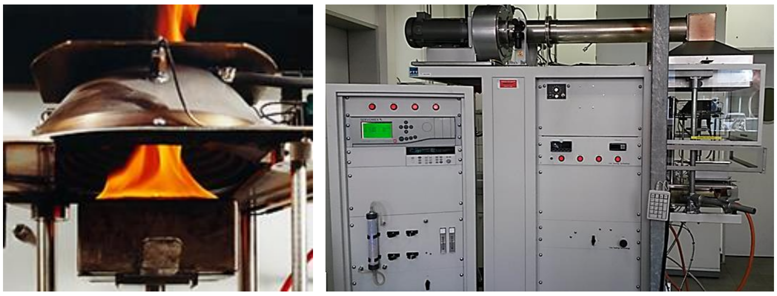


Figure 17 – Cone Calorimeter used in Laboratory at BAM [46]

A standardized specimen size of 100 mm x 100 mm and a maximum thickness of 50 mm can be irradiated up to 100 $kW/m^2$ by the heat source in the Cone Calorimeter. The thermal stress simulates the consequences of heat radiation from burning materials to a not yet burning material and generates the pyrolysis on the material surface. The ignition of the pyrolysis gases is supported by a 10 kV spark ignition. In the Cone Calorimeter a mass loss scale for burning material specimens and a special exhaust system with an adjusted flow rate of 0.024 $m^3/s$ for the smoke gas analysis are also installed. Figure 18 shows the components of a Cone Calorimeter.

In the sector of passenger transportation the Cone Calorimeter is an essential part of the fire safety requirements. In detail the Cone Calorimeter is required by material fire tests of 'Fire Protection on Railway Vehicles' according to EN 45545-2 [34] and 'Fire Test Procedures Code' of the International Maritime Organization according to IMO FTP Code [47] as well as of 'Federal Aviation Regulations' according to FAR 25.853 [36] and 'Joint Aviation Regulations' according to JAR 25.853 [37].

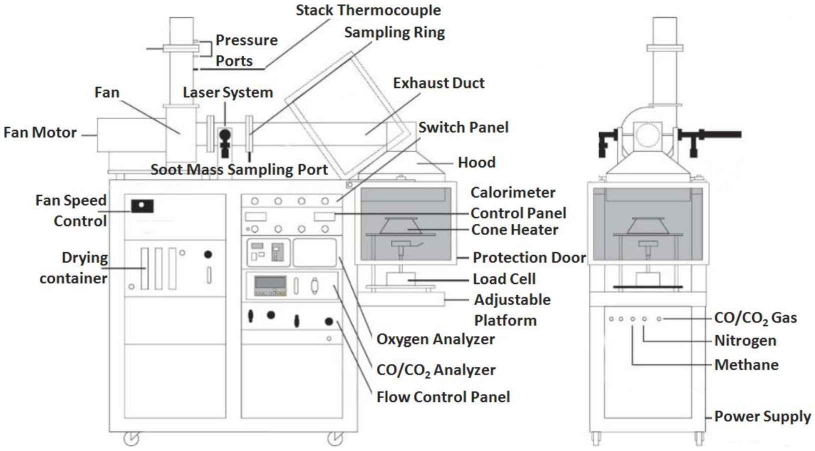



Figure 18 – Testing Apparatus of Cone Calorimeter [Compare with 48]

The determination of heat release is generally based on the 'Cone Calorimeter Method' of EN ISO 5660-1 [31]. The test duration amounts to 20 min in which the average rate of heat emission at time t (ARHE(t)) is to determine. Maximum average rate of heat emission (MARHE) is then the maximum value of ARHE(t) [34].

Table 12 shows the MARHE-values of bus interior materials examined. The irradiance level set for the Cone Calorimeter tests derived from the EN 45545-2 which regulates the fire safety requirements and the testing conditions according to EN 45545 for rail materials applied [34].

Table 12 – Results of Cone Calorimeter Tests

| Results of the Cone Calorimeter tests | | | |
|---|---|---|---|
| **Sample** | **Test Series** | **Irradiance [kW/m²]** | **MARHE [kW/m²]** |
| Ceiling I | 1 | 50 | 247,2 |
| Ceiling I | 2 | 50 | 215,7 |
| Ceiling II | 1 | 50 | 307,7 |
| Ceiling II | 2 | 50 | 255,5 |
| Flooring | 1 | 25 | 1,6 |
| Floor covering | 1 | 25 | 32,5 |
| GRP part | 1 | 50 | 258,5 |
| GRP part | 2 | 50 | 280,9 |
| Insulation | 1 | 50 | 334,5 |
| Insulation | 2 | 50 | 309,0 |
| Seat foam | 1 | 25 | 309,2 |
| Seat foam | 2 | 25 | 166,7 |
| Side panel | 1 | 50 | 64,8 |
| Side panel | 2 | 50 | 54,2 |

### 3.1.3 Smoke Density Chamber

The Smoke Density Chamber (SDC) is a testing instrument designed and developed for the determination of smoke properties [49]. The apparatus contains a sealed test chamber with a volume of ca. 0.5 m³ and is equipped with photometric measurements as shown in Figure 19. Specimens can be exposed either by a horizontal thermal irradiation up to 50 kW/m² according to the EN ISO 5659-2 [32] or by a vertical thermal irradiation of 25 kW/m² according to the ASTM E662 [49]. In addition a pilot flame can be activated if required. The photometric scale is similar to the optical scale of human vision. Smoke characteristics to be measured in the SDC are the light transmission (T) and the specific optical density ($D_S$) as well as the cumulative value of specific optical densities in the first 4 min of testing (VOF4) and the mass referenced optical density (MOD). An additional mounted FTIR-spectrometer (Fourier Transform Infrared spectrometer) analyse qualitatively and quantitatively smoke gas components. The FTIR-spectrometer can analyse smoke gas components and their concentrations. The SDC is an essential part in material fire safety requirements of passenger transport systems, such as required for rail vehicles according to EN 45545-2 [34], for ships according to IMO FTP Code [47] and airplanes according to FAR/JAR 25.853 [36 and 37].

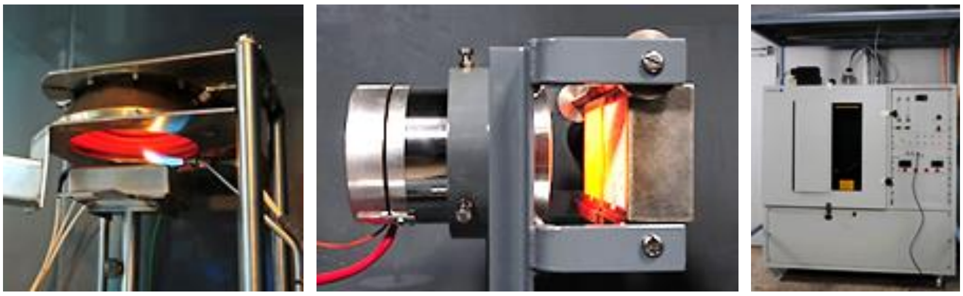


Figure 19 – Smoke Density Chamber used in Laboratory at BAM [50]

Specimens to examine in the SDC are sized to 75 mm x 75 mm x thickness. In this test series the concentrations of eight toxic smoke gas components were measured as required for EN 45545-2. In detail carbon dioxide ($CO_2$), carbon monoxide (CO), hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen cyanide (HCN), sulphur dioxide ($SO_2$) and nitrous gases ($NO_X$) are analysed. Table 13 summarizes the concentrations measured of bus interior materials tested.

The concentration measurements indicate that several materials reach rapidly lethal smoke concentrations levels. Diagrams of the smoke gas concentrations and completed by the lethal levels and the level of intoxications symptoms are attached in Annex IV for all interior material samples tested.

Table 13 – Concentrations of Toxic Smoke Gas Components Measured

| Concentrations of Toxic Smoke Gas Components Measured | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **Analyse time** | **$CO_2$ [ppm]** | **CO [ppm]** | **$SO_2$ [ppm]** | **$NO_x$ [ppm]** | **HBr [ppm]** | **HCl [ppm]** | **HF [ppm]** | **HCN [ppm]** |
| Ceiling I | 4 min | 11900 | 668 | 0 | 87 | 0 | 1013 | 1 | 39 |
| | 8 min | 14700 | 967 | 0 | 97 | 1 | 923 | 0 | 40 |
| Ceiling II | 4 min | 16500 | 762 | 52 | 111 | 0 | 1528 | 3 | 33 |
| | 8 min | 20000 | 984 | 40 | 149 | 0 | 1385 | 0 | 40 |
| Floor covering | 4 min | 7500 | 793 | 0 | 31 | 0 | 4050 | 2 | 3 |
| | 8 min | 10100 | 931 | 0 | 8 | 0 | 3572 | 4 | 5 |
| GRP part | 4 min | 19800 | 682 | 0 | 0 | 4 | 0 | 0 | 10 |
| | 8 min | 35700 | 1122 | 0 | 0 | 7 | 2 | 0 | 16 |
| Insulation | 4 min | 5900 | 99 | 5 | 73 | 0 | 1 | 0 | 36 |
| | 8 min | 6900 | 168 | 25 | 54 | 0 | 3 | 4 | 52 |
| Seat foam | 4 min | 14200 | 23 | 1 | 82 | 0 | 0 | 0 | 5 |
| | 8 min | 15800 | 53 | 0 | 74 | 0 | 1 | 0 | 7 |
| Side panel | 4 min | 3600 | 1076 | 80 | 0 | 1 | 0 | 0 | 167 |
| | 8 min | 4400 | 2004 | 41 | 1 | 0 | 0 | 0 | 245 |

The optical density in smoke gases investigated was determined by the parameters $D_{S,max}$ (peak of specific optical density) and VOF4 (cumulative value of specific optical densities in the first 4 min of testing) according to the EN 45545-2 [34]. The results regarding optical density are summarised in Table 14. The measured smoke density values indicate that almost all tested materials release high amount of opaque smoke.

Table 14 – Optical Density measured

| Optical Density measured | | | |
|---|---|---|---|
| **Sample** | **Test series** | **$D_{S,max}$** | **VOF4** |
| Ceiling I | 1 | 839,5 | 2389,9 |
| Ceiling I | 2 | 803,9 | 2013,6 |
| Ceiling II | 1 | 601,8 | 2133,6 |
| Ceiling II | 2 | 622,5 | 2224,8 |
| Floor covering | 1 | 620,1 | 1948,3 |
| Floor covering | 2 | 695,4 | 2104,8 |
| GRP part | 1 | 797,5 | 1194,1 |
| GRP part | 2 | 1320,0 | 1843,9 |
| Insulation | 1 | 127,5 | 260,8 |
| Insulation | 2 | 70,0 | 233,5 |
| Seat foam | 1 | 100,5 | Not required |
| Side panel | 1 | 453,8 | 918,7 |
| Side panel | 2 | 560,2 | 1102,7 |

In conclusion of examining smoke properties it must be said that fire safety measures of road vehicles are not adequate regarding minimizing hazards of smoke. Especially the production, density and toxicity of smoke seen in tests of such materials are weak points. In addition, when comparing against EN 45545 requirements the materials investigated would not meet Hazard Level 1 which is the lowest requirement class for rail vehicles as usually applied for e.g. trams.

### 3.1.4 Single-flame Source Test

The Single-flame Source Test is a testing instrument to determine the ignitability of a material and its lateral flame spread in vertical direction according to EN ISO 11925-2 [51] as shown in Figure 20. The test apparatus is based on the German Kleinbrenner according to DIN 4102 [52]. For building products the Single-flame Source Test is the fundamental test method (construction products directive according to 89/106/EEC [53]) and is also required for filter materials (e.g. used in ventilation and heating system) in rail vehicles according to EN 45545-2 [34].

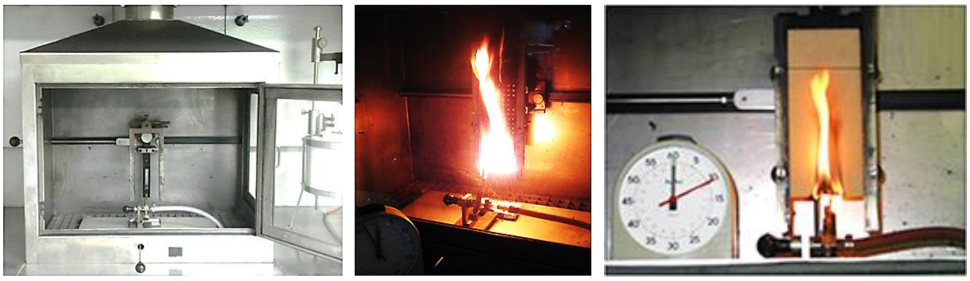


Figure 20 – Single-flame Source Test used at BAM [54]

In the Single-flame Source Test the material specimen, sized to 250 mm x 90 mm x material thickness, is attached in a U-shaped specimen holder. During the test procedure the material specimen is flamed for 30 s at the lower edge by a 20 mm high propane gas flame. In addition a sheet of filter paper is positioned under the specimen holder to check falling flaming debris during the test procedure.

The requirements of the Single-flame Source Test are succeeded when the flame top could not reach the height of 150 mm within 60 s and if the filter paper was not ignited by burning droplets during the test procedure. In Table 15 the results of the tested bus interior materials are shown.

Table 15 – Measurements in the Single-flame Source Test

| Measurements in the Single-flame Source Test | | | | |
|---|---|---|---|---|
| **Sample** | **Ignition [y/n]** | **Mark reached [s]** | **Ignition of filter paper [y/n]** | **Externally suppressed after [s]** |
| Ceiling I | Yes | 27 | No | 180 |
| Ceiling II | Yes | not | No | 90 |
| Dashboard | Yes | not | No | 90 |
| Floor covering | No | not | No | Not needed |
| GRP part | Yes | not | No | 90 |
| Insulation | Yes | 10 | No | 30 |

## 3.2 Experiments in Real-Scale

In addition to small-scale material tests fire tests were performed on single interior parts as well as in different compartments of an entire bus. These real-scale experiments were mainly used to examine the fire safety performance of parts which are essential for the fire propagation in a bus and to investigate the fire behaviour including smoke within different bus compartments.

### 3.2.1 Passenger Seats

Passenger seats represent the highest number of bigger interior parts in buses. Thus, the fire safety performance of passenger seats significantly influences the fire development in passenger cabins and was therefore extra examined. In detail seats of different bus types were separately investigated in a fire test series. For comparison a passenger seat of a train and a driver seat of a car were tested as well.

In the test series passenger seats were ignited by burning newspaper on the seating surface to simulate arson there. In detail a paper pillow standardised according to DIN 5510-2 [55] in build-up, size and weight was used in each seat fire test. The paper pillow consists of eight paper sheets measuring 42 cm x 60 cm. Seven sheets are formed to approximately 8 cm paper balls by scrunching and an eighth sheet is folded as an envelope for containing the balls. The paper pillow must be complemented to a weight of 100 g by adjusting the seventh paper ball. Finally the paper pillow must be closed by staples as shown in Figure 21.

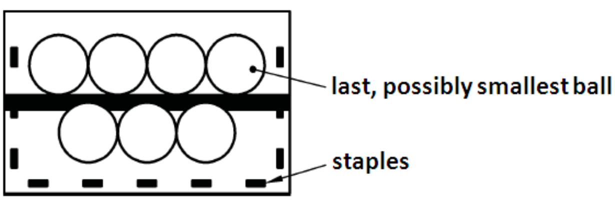



Figure 21 – Paper Pillow according to DIN 5510-2 [55]

Generally DIN 5510 is the German standard for ‘Preventive fire protection in railway vehicles’ [55] and requires this test method for passenger seats. For road vehicles this fire test is usually not required.

For assessing the outcome of fire tests the calorimeter test method was chosen in which the fire behaviour based on heat emission is analysed. The calorimeter tests were performed in the test apparatus of a Single Burning Item (SBI) according to EN 13823 [56]. The SBI is primary a testing instrument for specific building materials and can also be used for calorimeter tests to monitor the burning behaviour by recording the heat release rates. In Figure 22 the used SBI is shown from outside on the left and from inside on the right.

Figure 22 – SBI at BAM [49]

A passenger seat compliant to UNECE R 118 [57] of a city bus was tested first. Generally UNECE R 118 is the fire safety standard for bus interior materials [26]. A bus operator provided this passenger seat for testing since it remained unscathed in a bus fire next to a fire brigade station as the fire could be quickly extinguished before total loss as shown in Figure 23 on the right. Since the bus was registered in 2005, it can be assumed that this passenger seat is from 2005 as well. The passenger seat itself was more or less designed as a plastic seat shell most likely produced per injection moulding process. Additionally a thin-cushioned seat cover was fitted on the seating surface and the backrest. A handle holder was mounted on the top of the backrest.

Figure 23 – Bus Passenger Seat compliant to UNECE R 118 tested and the Donor Bus [58]

In the calorimeter test the bus passenger seat was easily ignited by the inflamed paper pillow. After 1 min elapsed the backrest was burning as shown in the second picture of Figure 24. After almost 2 min elapsed the flames already reached the tip of the backrest as shown in the third picture of Figure 28. After 5 min elapsed the backrest and most of the seating surface were completely flaming as shown in the fourth picture of Figure 24. At 20 min elapsed the passenger seat was still burning, however, the backrest was already collapsed as shown in last picture of Figure 24.


Figure 24 – Bus Passenger Seat compliant to UNECE R 118 in Calorimeter Test

The heat release rates during the fire test are shown in the diagram of Figure 25. In addition the HRR curve of a paper pillow is implemented in the diagram as well to indicate that the heat released by the paper pillow is negligibly low in contrast to the HRR curve recorded during the test.

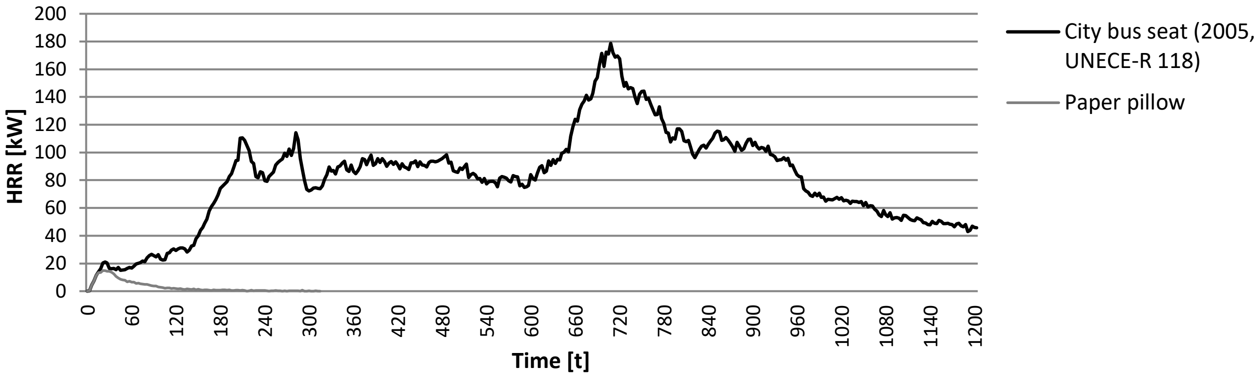



Figure 25 – HRR Diagram of Bus Passenger Seat compliant to UNECE R 118

A passenger seat compliant to protection degree 3 of DIN 5510 [55] as shown in Figure 26 on the left was tested second. Normally interior parts of buses do not conform to such a rail standard but the operator replaced passenger seats in their buses and trams against passenger seats conforming to DIN 5510 as the new corporate design was uniformly implemented in 1999. Thus, it can be assumed that this passenger seat is from 1999 as well. Basically a complex construction consisting of different plastic components and fibreglass are applied in this seat. On the backrest and on the seating surface an upholstered seat cover showing the unique operator design is fitted as shown in Figure 26 on the left.

Figure 26 – Bus Passenger Seat compliant to DIN 5510 tested and Donor Bus

In the calorimeter test the passenger seat was slightly ignited by the burning paper pillow only. After 1 min elapsed the flames reached the tip of the backrest as shown in the second picture of Figure 27. However, when the paper pillow was burnt off the fire was going out slowly as shown in the third picture of Figure 27. When deemed extinct the passenger seat was successfully tried to reignite by a Bunsen burner for demonstrating that behind the seat upholstery this passenger seat is also able to burn as shown in the last pictures of Figure 27.


Figure 27 – Bus Passenger Seat compliant to DIN 5510 in Calorimeter Test

The heat release rates during the fire test are shown in Figure 28. The dotted line highlights the section after reignition which also states that some minutes were needed to reignite the seat as can be seen at ca. 7 min elapsed in diagram of Figure 28. The part of a paper pillow is implemented in the diagram as well to indicate that the paper pillow is the main portion of total HRR curve recorded until reignition of the seat.

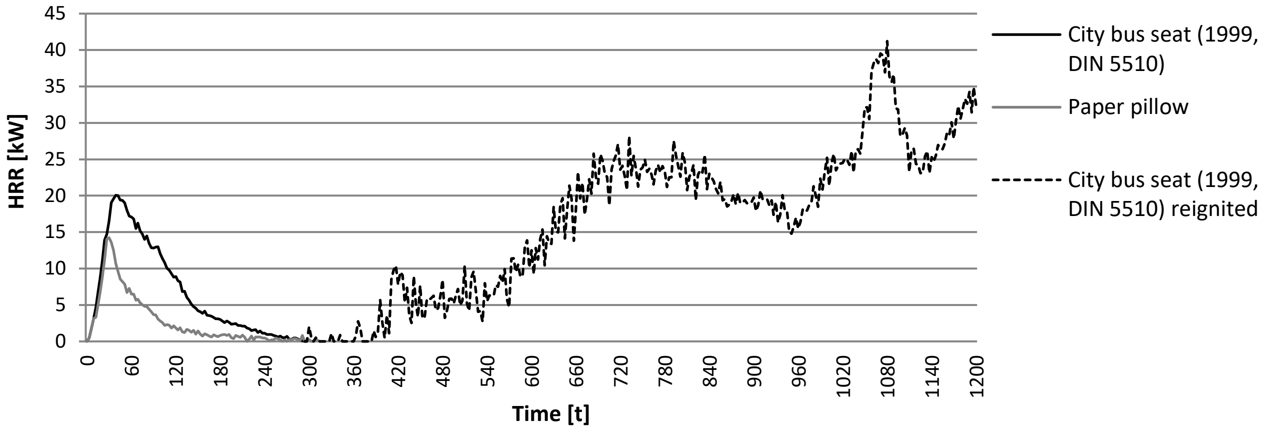



Figure 28 – HRR Diagram of Bus Passenger Seat compliant to DIN 5510

A coach passenger seat conforming to UNECE R 118 [26] replicated by seat foam parts normally used for the upholstery of comfortable passenger seats in coaches was tested next. Predominantly such passenger seats are based on a steel frame with upholstery coated by a seat cover. Thus only the seat foam which passed the set of material fire tests required by UNECE R 118 [26] was tested as shown in Figure 29. The seat foam was provided from an automotive supplier. Both the foam part for the backrest and for the seating surface were cut and put together in an angle of 90°. The backrest was additionally reinforced with a steel upright at the back side as shown in Figure 29 on the left.

Figure 29 – Coach Passenger Seat compliant to UNECE R 118 prior to testing

Within the first 30 s of the test the paper pillow was burning only. However, as soon as ignited the seat went into a quick combustion process. Already at 3 min elapsed the complete seat was burning as shown in third picture of Figure 30. At 5 min elapsed the passenger seat was collapsed meanwhile and still burning. After 20 min elapsed the flames went finally out since the complete seat was burnt off as shown in the last picture of Figure 30.


Figure 30 – Coach Passenger Seat compliant to UNECE R 118 in Calorimeter Test

The heat release rates during the fire test are shown in the diagram of Figure 31. In addition the HRR curve of a paper pillow is implemented in the diagram as well to indicate that the heat released by the paper pillow is negligibly low in contrast to the HRR curve recorded during the test.

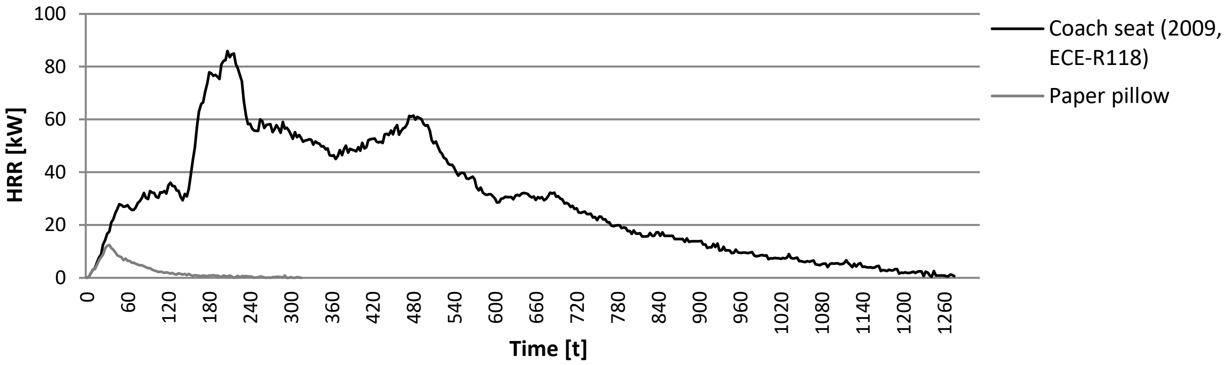



Figure 31 – HRR Diagram of Coach Passenger Seat compliant to UNECE R118

A train passenger seat conforming to Hazard Level 2 of EN 45545-2 [34] replicated by seat foam parts normally used for the upholstery of comfortable train seats and coated with a typical seat cover from German trains was tested as well. The combination of foam and cover have passed the material requirements according to EN 45545-2 which has superseded the German fire safety standard DIN 5510 in 2013 with more stringent material fire requirements. For testing the foam parts were prepared in the same way as the coach passenger seat. In difference the seat cover was additionally fitted over the backrest and seating surface as shown in Figure 32 on the right.

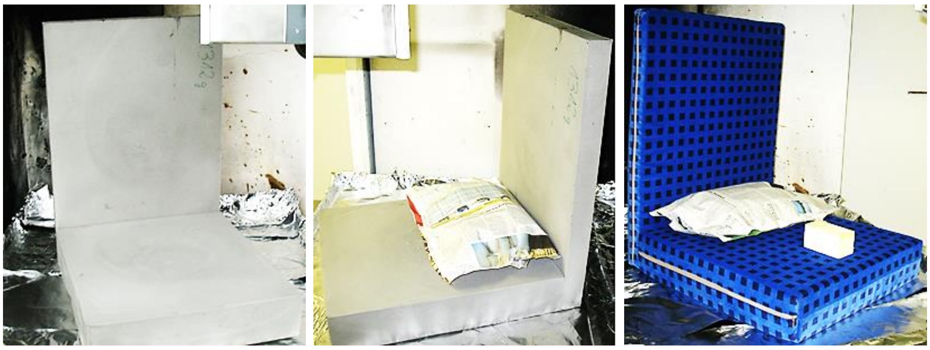


Figure 32 – Train Passenger Seat compliant to EN 45545-2 prior to testing

In the calorimeter test the train passenger seat did not catch fire from the paper pillow burning. After 1 min elapsed the paper pillow and just a small stripe on the backrest cover were burning only. This is also the point in time in which approximately the peak of HRR was reached. Afterwards the fire was just decreasing as shown in the third picture of Figure 33. At 5 min elapsed the flames were nearly gone out as visible in the fourth picture of Figure 33. When the flames were deemed extinct at 18 min elapsed the passenger seat was tried to reignite by a Bunsen burner as shown in the last picture of Figure 33. However, the ignition tried with harder means failed.


Figure 33 – Train Passenger Seat compliant to EN 45545-2 in Calorimeter Test

The heat release rates during the fire test are shown in Figure 34. The part of a paper pillow is implemented in the diagram as well to indicate that the paper pillow is the main portion of total HRR curve recorded. The HRR peaks visible in the diagram starting from ca. 18 min elapsed are made by a Bunsen burner when tried to ignite the seat with harder means at test end.

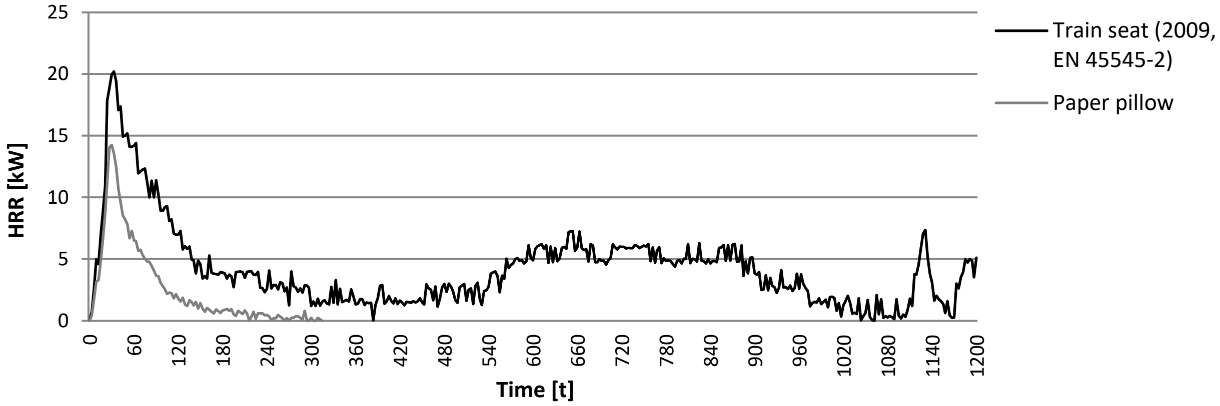



Figure 34 – HRR Diagram of Train Passenger Seat compliant to EN 45545-2

In addition to the fire tests with the passenger seats a complete driver seat from a car conforming to ISO 3795 [59] as shown in Figure 35 was investigated as well, mainly to examine the differences between passenger seats in buses and driver seats in cars. Principally this comfortable driver seat consists of a complex steel frame and thick upholstery which is made of PUR foam fitted with a seat cover. The surface of the seat was rough. In contrast to the passenger seats tested before the driver seat had a head rest on top. The driver seat was manufactured from a European car manufacturer in 2004.


Figure 35 – Car Driver Seat compliant to ISO 3795 prior to testing

In the calorimeter test the driver seat was easily ignited by the burning paper pillow. At 1 min elapsed the backrest of the seat and at 2 min elapsed the driver seat were completely burning as shown in the second and third picture of Figure 36. Later the head rest and parts of the backrest dropped down. Afterwards the driver seat was still burning although the fire was tried to manually interrupt several times since the fire became critical for the measurement technique. Firstly a $CO_2$ fire extinguisher was unsuccessfully applied and subsequently a high pressure water sprayer was used.


Figure 36 – Car Driver Seat compliant to ISO 3795 in Calorimeter Test

The heat release rates recorded during the fire test are shown in the diagram of Figure 37. In addition the HRR curve of a paper pillow is implemented which seems to be almost invisible and therefore indicates that the heat release amount of the paper pillow is negligibly low compared to the portion of the driver seat. The first HHR decrease at ca. 2 min elapsed was caused by the exhaust air unit which was manually accelerated during the fire test process to protect the measurement technique in the test apparatus against the extreme amounts of heat released. The doted curve section highlights the fire suppression activities mentioned earlier. Thus, the $CO_2$ extinguisher was responsible for the first main HRR decrease at ca. 3 min elapsed and the water sprayer for the fluctuation afterwards at ca. 6 min elapsed.

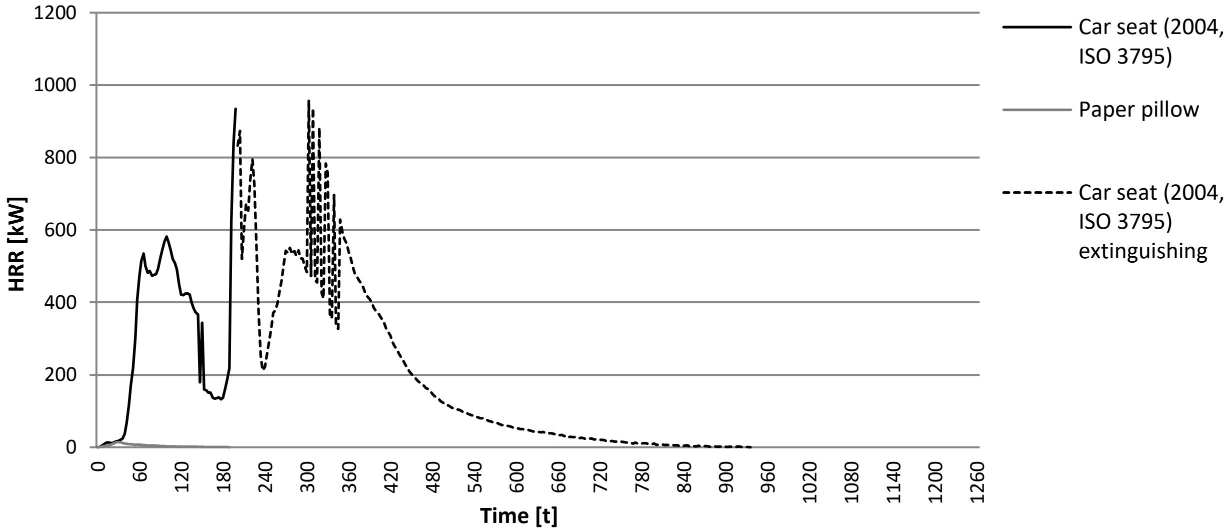



Figure 37 – HRR Diagram of Car Driver Seat compliant to ISO 3795

### 3.2.2 Engine Compartments Test Rig

Most bus fires start in engine compartments [33]. Therefore investigations on fire scenarios in engine compartments were of interest. Since the Swedish research institute SP (now RISE) was in the beginning of developing a test rig for fire suppression systems in bus engine compartments including reasonable fire scenarios for the SP-Method 4912 [60] at this time, SP's offer to cooperate in this field was accepted. Generally the engine compartment test rig compliant to SP-Method 4912 [60] is a testing apparatus for examining the performance of fire suppression systems for bus engine compartments. Thus, fire tests simulating and assessing different fire scenarios in engine compartments were performed in cooperation with SP fire science researchers and some supporting manufacturers of fire suppression systems. At this time the engine compartment test rig was in an early stage as shown in Figure 38 on the right in which fire scenarios and ventilation modes were still discussed. Therefore many fire tests were run to assess different test conditions. Compared to the final test rig, the setup used for testing, such as shown in Figure 38, was nearly the same except some obstruction modifications.

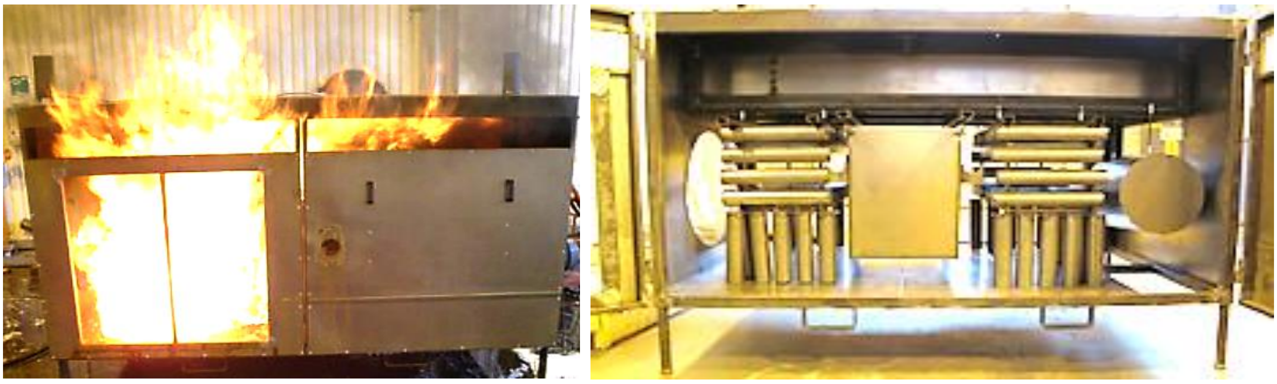


Figure 38 – Engine Compartment Test Rig compliant to SP-Method 4912

The SP-Method 4912 is now largely a part of a directive for buses which defines the requirements for fire suppression systems in bus engine compartments. Generally all the fire tests performed demonstrate that the environment of an engine compartment tends to be well-ventilated which entails the development of very high temperatures, partly exceeding 1000 °C. Especially spray fires based on diesel fuel or hydraulic oil are able to produce extremely destructive fires.

Concerning fire suppression in engine compartments the orienting tests performed has principally demonstrated that such systems would be a reasonable solution for minimizing fire hazards not only in the engine compartment but also for the entire bus. However, the tests have also shown that there are fire scenarios possible in which most fire suppression approaches would probably fail or in which reignition occurs after suppression. Thus, the strict testing requirements of SP-Method 4912 based on several challenging fire scenarios are an effective instrument to improve the reliability of fire suppression systems for engine compartments and especially for preventing many bus fires.

### 3.2.3 Bus Engine Compartment

In addition to fire tests conducted in laboratory conditions several fire tests were performed to investigate the fire behaviour and the propagation of fire and smoke in the engine compartment and also in the passenger cabin under conditions of a real bus. The test bus was a decommissioned city bus of a local public transport company and was still fully operational during fire tests. The mileage driven amounts to almost 900,000 km. In Table 16 its data from registration certification are summarised.

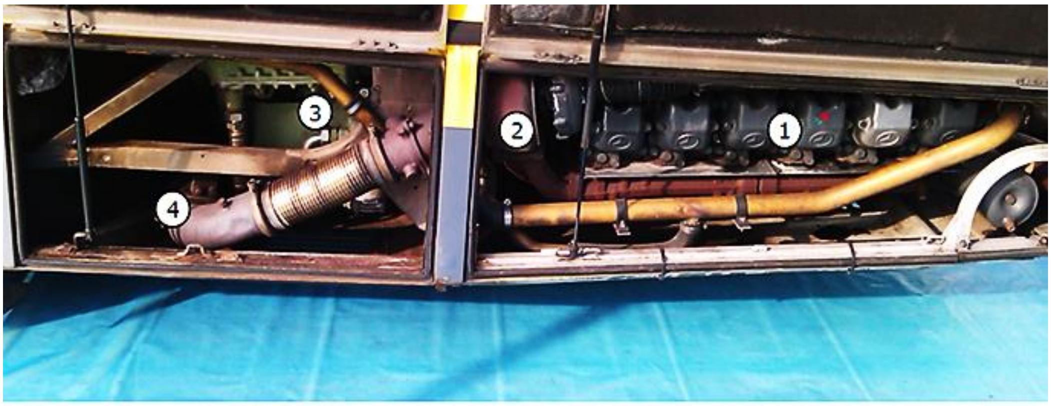
Table 16 – Test Bus Data from Registration Certification

| **Test Bus Data from Registration Certification** | |
|---|---|
| **Data** | **Values** |
| Registration Date | 07/ 1995 (production period: 1990-2001) |
| Manufacturer/ Type | Mercedes/ O 405 N |
| Engine Power | 184 kW/ 250 HP |
| Length | 11.91 m |
| Width | 2.50 m |
| Height | 2.94 m |
| Seating Capacity | 31 |
| Standing Capacity | 71 |
| Curb Weight | 10,350 kg |
| Maximum Permissible Weight | 18,000 kg |

Fire tests with the test bus were performed at a test stand normally used for flaming of fuel tanks at the test site of BAM as shown in Figure 39. Regarding the size and also the necessary safety measures it was ideal for performing such fire tests. In detail the concrete basin of this test stand could be used to collect spilled operation liquids and fire suppression agents on the one hand. On the other hand the blast walls which normally minimise the consequences of a tank explosion in horizontal direction were used to protect the analysis technique against heat radiation behind the bus. This test stand also featured hydrants for extinguishing nearby just for the case the fire propagates to an uncontrolled fire while testing. In addition all fire tests were observed by BAM technical support and fire service.

Figure 39 – Test Bus at Fire Test Stand of BAM

In the test bus the engine compartment is located at the vehicle end behind the rear axle and is thus placed directly under the floor of the passenger cabin. This is a typical design for buses. The powertrain components including the engine are positioned on the left side in the engine compartment as shown in Figure 40.




1 Engine block 3 Automatic gearbox
2 Turbocharger 4 Manifold

Figure 40 – Engine and Powertrain Components of Test Bus

Most maintenance elements of the engine as well as the cooling fan are located at the back of the engine compartment as shown in Figure 41 on the left. The air intake ahead of the cooling fan is positioned on the right side of the bus back and is hidden behind a ventilation grid as shown in Figure 41 in the middle and on the right.

Figure 41 – Outer Maintenance Flaps of Engine Compartment at Test Bus

In the back of the passenger compartment two maintenance flaps provide access to the engine block and the powertrain components as shown in Figure 42. Behind the flaps the engine compartment is completely overstuffed like the back of the engine bay. Figure 42 also indicates that the flaps might provide insufficient fire resistance.

Figure 42 – Inner Maintenance Flaps of Engine Compartment in Passenger Cabin

Regarding ventilation aspects there is no air conditioning in the test bus. Instead two ventilation flaps are installed at the passenger cabin ceiling which are electrically controlled from the cockpit. In addition three poorly sealed double doors on the right vehicle side, two small hopper windows located in the top part of the sidewalls above the rear wheels on both vehicle sides and a sliding window at the driver's cockpit must be considered for ventilation scenarios as well.

In preparation for fire tests the test bus was equipped with a lot of measurement technique. In total 48 thermocouples and two sampling points for FTIR smoke analysis as well as three smoke detectors and two cameras for recording the fire development inside were installed in the passenger compartment as shown in Figure 43. The sampling points for the FTIR smoke gas analysis were located in a height of 1.60 m above the flooring to investigate the toxicity of smoke gases on a level on which approximately most passengers take their breathing air from. In longitudinal direction the sampling points were located over the front and back axles in escape routes as indicated by black pentagons in Figure 43.

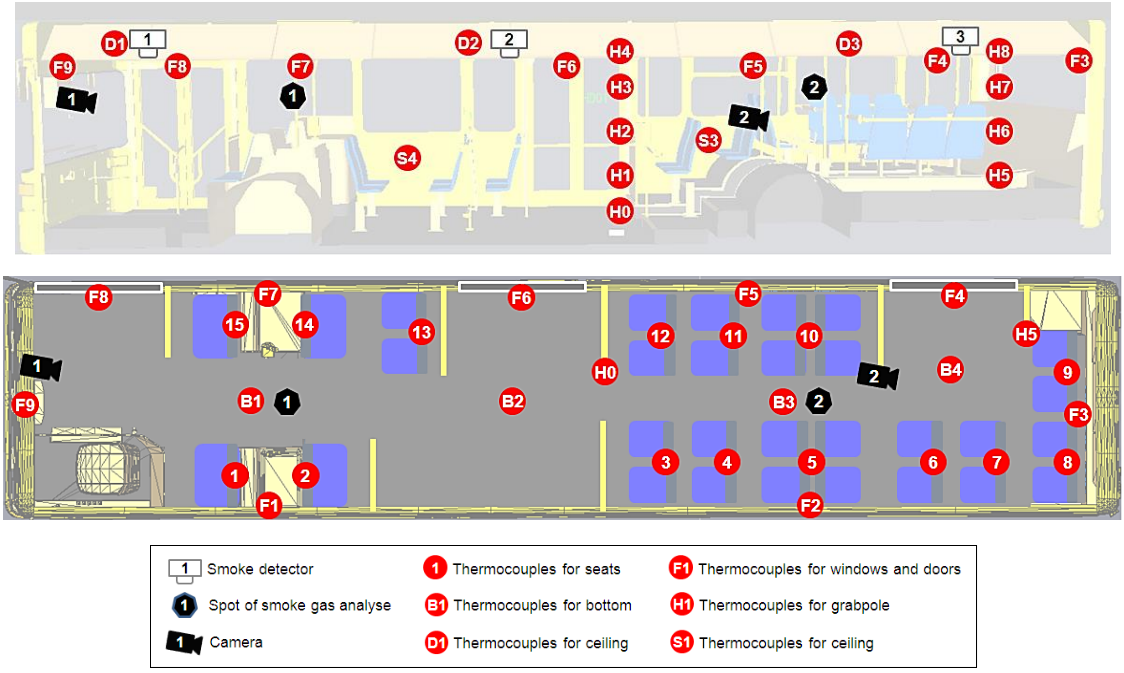



Figure 43 – Measurement Technique in Passenger Cabin of Test Bus

Based on practical experiences and knowledge gained from fire tests in the engine compartment test rig at SP test lab additional fire tests within the engine compartment of the test bus were conducted. These tests were fundamentally focused on the fire behaviour in the engine bay as well as on the fire and smoke penetration into the passenger cabin under different but real operation conditions. In addition the fire tests were completed by fire detectors and fire suppression systems to preserve the bus and the operability of its engine on one hand and to examine the quality and promptness of those systems on the other hand. In sum six different fire suppression systems provided by four manufacturers were examined as summarised in Table 17.

Table 17 – Fire Suppression Systems Tested

| Fire Suppression Systems Tested | | | | |
|---|---|---|---|---|
| **Tested system** | **Extinguishing system** | | | |
| | **Fabricator** | **Fire suppression agent** | **Volume** | **Nozzles** |
| A | Dafo | Water spray with foam (Forrex) | 15 l (1 bottles) | 16 |
| B | Firedect | Water mist with additives | 7 l (1 bottles) | 10 |
| C | Fogmaker | Water mist with foam and additives | 13 l (2 bottles) | 14 |
| D | Kidde | Liquid (Clean Agent Novec 1230) | 4 l (1 bottles) | 4 |
| E | Kidde | Dry chemical (BC 101 powder) | 10 kg (1 bottles) | 5 |
| F | Kidde | Dry chemical (BC 101 powder) | 10 kg (1 bottles) | 2 |

The fire scenarios were mainly based on fire tests required by the Swedish standards SBF 128 [61] and the SP-Method 4912 [60]. Both contain test procedures for examining fire suppression systems of bus engine compartments. The SBF 128 describes a fire suppression test in a real bus engine compartment. Therefore the fire scenario I was based on SBF 128 as shown in Table 18. In this scenario the fire load is given by several pool fires which are equally distributed over the engine compartment. In total a 3 kg mixture of 3 l dry sawdust drenched with a burnable liquid consisting of 50 % diesel fuel, 25 % hydraulic oil and 25 % raw industrial oil [compare with 61] was portioned into nine pans. In addition 200 g portions of cotton pulp drenched with spirits were also equally distributed over the engine compartment for this fire scenario [61]. The fire suppression system itself was manually activated one minute elapsed after ignition of fire sources.

Table 18 – Comparison between SBF 128 and Fire Scenario I[61]

| Comparison between SBF 128 and Fire Scenario I | | |
|---|---|---|
| **Test conditions** | **SBF 128** | **Fire scenario I** |
| Engine preheating | 15 min at idle and<br>5 min at 1800 rpm | 15 min at idle and<br>5 min at 1800 rpm |
| Fire sources | 3 kg mixture of sawdust and burnable liquids, 200g cotton pulp drenched with spirits | 3 kg mixture of sawdust and burnable liquids, 200g cotton pulp drenched with spirits |
| Engine speed while testing | not specified | 1500 rpm |

The challenge of fire scenario I concerning fire suppression mainly results from the high fire load of distributed fire sources as shown in Figure 44 as well as from the strong airflow caused by the cooling fan. The latter accelerates significantly the fire growth in the engine compartment and might lead to the effect that during the suppression process the agent is probably blown away before reaching all hidden corners in the engine compartment.

Figure 44 – Fire Scenario I of Engine Compartment Fire Tests

In fire scenario II the requirements of Test 4 from SP-Method 4912 simulating small and hidden fires were transferred into a real engine compartment as shown in Table 19. In particular three 50 kW pool fires generated by 300 ml mixture of 50 % diesel fuel and 50 % heptane shall be applied [compare with 60]. The fire suppression system was manually activated when one minute had elapsed after ignition of fire sources.

Table 19 – Comparison between Test 4 of SP-Method 4912 and Fire Scenario II[60]

| Comparison between Test 4 of SP-Method 4912 and Fire Scenario II | | |
|---|---|---|
| **Test conditions** | **Test 4 of SP-Method 4912** | **Fire scenario II** |
| Engine preheating | No real engine, preheating by flaming | 5 min at 1800 rpm |
| Fire sources | Three 50 kW pool fires | Three 50 kW pool fires |
| Engine speed while testing | No real engine | Idle |

The challenge of fire scenario II concerning fire suppression consists of small and hidden fires in remote areas as shown in Figure 45 which are probably hard to reach by suppression agents. Especially fire suppression agents operating based on the evaporation effect for cooling the fire and for displacing air by expanding enormously might be less effective on small and hidden fires since such agents usually need hot and intensive fires for successful fire suppression.

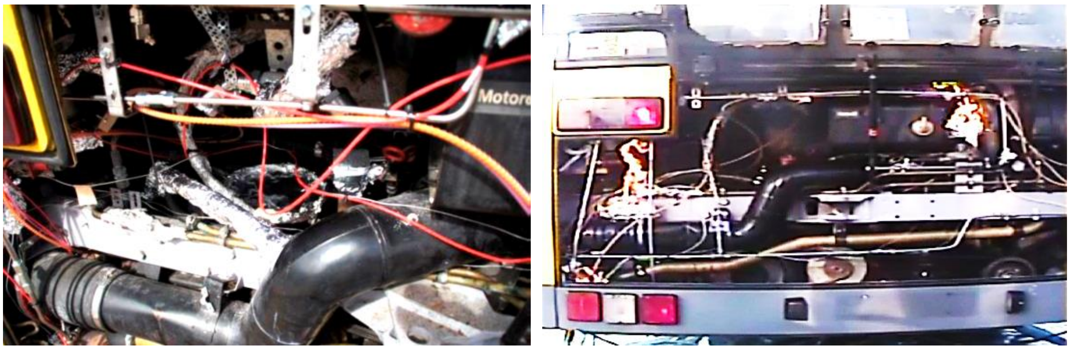


Figure 45 – Fire Scenario II of Engine Compartment Fire Tests

In fire scenario III a spray fire according to Test 13 of the SP-Method 4912 was applied to simulate leaking of a fuel pipe in case of fire as summarised in Table 20. Normally when operating, hydraulic oil and fuel in pipes are under pressure. In case of leaking these liquids can ignite on hot engine parts such as the turbo charger. For these tests the original pressure sprayer from the engine compartment test rig of SP laboratory was used. The fuel was based on a 1.5 l fluid mixture of 60 % diesel oil, 20 % hydraulic oil and 20 % of gasoline [60]. In the pressure sprayer tank the fuel was preloaded up to 2 bar. While testing the fuel mixture was sprayed into the turbo charger area within the engine compartment by a special nozzle. The flow rates of fuel was adjusted to 10 g/ min of fuel.

Table 20 – Comparison between Test 13 of SP-Method 4912 and Fire Scenario III[60]

| **Comparison between Test 13 of SP-Method 4912 and Fire Scenario III** | | |
|---|---|---|
| **Test conditions** | **Test 13 of SP-Method 4912** | **Fire scenario III** |
| Engine preheating | No real engine | 5 min at 1800 rpm |
| Fire sources | Spray fire | Spray fire |
| Engine speed while testing | No real engine | Idle |

The challenge of fire scenario III concerning fire suppression is based on the extremely hot spray fire combined with the airflow operating in the engine compartment. This combination produces a well burning mixture of fuel and oxygen which generates a huge destructive fire in the engine bay. To prevent the bus from catching fire uncontrolled, the pre-burn time was reduced to 10 s only. Figure 46 shows the fire within the pre-burn period.

Figure 46 – Fire Scenario III of Engine Compartment Fire Tests

In fire scenario IV the fire scenarios I, II and III are combined to a worst case fire scenario based on the pool fires from fire scenario I and II as well as the spray fire from fire scenario III as summarised in Table 21. In this fire scenario an extremely hot and destructive fire was generated which is comparable to Test 13 of SP-Method 4912 [60].

Table 21 – Comparison between Test 13 of SP-Method 4912 and Fire Scenario IV[60]

| Comparison between Test 13 of SP-Method 4912 and Fire Scenario IV | | |
|---|---|---|
| **Test conditions** | **Test 13 of SP-Method 4912** | **Fire scenario IV** |
| Engine preheating | No real engine | 5 min at 1800 rpm |
| Fire sources | Fire scenario III | Fire scenario I, II and III |
| Engine speed while testing | No real engine | Idle |

In contrast to fire scenario III the pre-burn time was additionally increased to 30 s. This scenario can be compared with an engine compartment fire grown unnoticed to a fully developed compartment fire which is able to penetrate easily into the passenger cabin. Thus, this fire constitutes an extremely challenging scenario for fire suppression systems and could be performed once only since the engine compartment was suffered afterwards. Figure 47 shows the fire within the pre-burn period on the left and while extinguishing on the right.


Figure 47 – Fire Scenario IV of Engine Compartment Fire Tests

In Table 22 test details and results of all fire suppression tests are summarised. In sum the fire suppression systems tested had problems to suppress the fire scenario I completely. All other fire scenarios were successfully suppressed. In conclusion it can be assumed that fire suppression systems conforming to SP-Method 4912 are able to suppress engine fires or would at least sufficiently delay the hazard of a fast bus fire. This is absolutely necessary since it took a few minutes to notice the fire, to stop the bus and to evacuate the passengers.

Table 22 – Details and Results of Fire Suppression Tests in Bus Engine Compartment

| Details and Results of Fire Suppression Tests in Bus Engine Compartment | | | | | |
|---|---|---|---|---|---|
| **Fire Test** | **Tested system** | **Fires scenario (origin)** | **Burn time elapsed before suppression** | **Engine speed** | **Fire Suppressed?** |
| 01 | D | I (SBF 128) | 60 s | 1800 rpm | No |
| 02 | C | I (SBF 128) | 60 s | 1800 rpm | No |
| 03 | B | I (SBF 128) | 60 s | 1800 rpm | No |
| 04 | A | I (SBF 128) | 60 s | 1800 rpm | No |
| 05 | E | I (SBF 128) | 60 s | 1800 rpm | No |
| 06 | E | II (Test 4 of SP-Method 4912) | 60 s | 900 rpm | Yes |
| 07 | C | II (Test 4 of SP-Method 4912) | 60 s | 900 rpm | Yes |
| 08 | A | II (Test 4 of SP-Method 4912) | 60 s | 900 rpm | Yes |
| 09 | A | III (Test 13 of SP-Method 4912) | 10 s | 900 rpm | Yes |
| 10 | C | III (Test 13 of SP-Method 4912) | 10 s | 900 rpm | Yes |
| 11 | F | III (Test 13 of SP-Method 4912) | 10 s | 900 rpm | Yes |
| 12 | F | IV (Fire scenario I, II and III) | 30 s | 900 rpm | Yes |

For monitoring the penetration of smoke into the passenger compartment installed cameras, smoke detectors and FTIR were used. The videos recorded during the fire suppression tests demonstrate that the resistance of the passenger cabin against smoke penetration from the engine compartment was mediocre only as shown in Figure 48 on the right. Smoke detectors in the passenger cabin alarmed sufficiently prompt at that moment when smoke was starting to emerge from the engine compartment. In conclusion the smoke detectors in the passenger compartment recognised the fires in the engine compartment a little bit faster than fire detectors located directly in the engine bay.

Figure 48 – Ignition and Smoke Penetration into Passenger Cabin in Fire Test 05

In all fire tests performed the total quantity of smoke penetrated into the passenger compartment was relatively low and its toxicity measured with the FTIR 2 was negligibly. It can be assumed that the pre-burn time of one minute in engine compartment fire tests was too short for analysing the toxic concentrations of smoke gas components entering the passenger cabin realistically. But it became evident that the engine compartment was not sufficiently sealed. Already in early stages of the fire development the smoke was able to penetrate into the passenger cabin as represented by fire scenario I and II.

Figure 49 shows the carbon dioxide concentrations measured at the FTIR 2 sampling point during Scenario I fire tests starting 10 min before ignition. Carbon dioxide was chosen as comparing parameter for smoke and its toxic components. The curves demonstrate that smoke was not in the passenger cabin before ignition while the engine was preheated by running at idle speed for 15 min and at 1800 rpm for further 5 min. Then the fire was started. In sum the carbon dioxide curves indicate the smoke penetration by enlarged amplitudes and increased fluctuations.

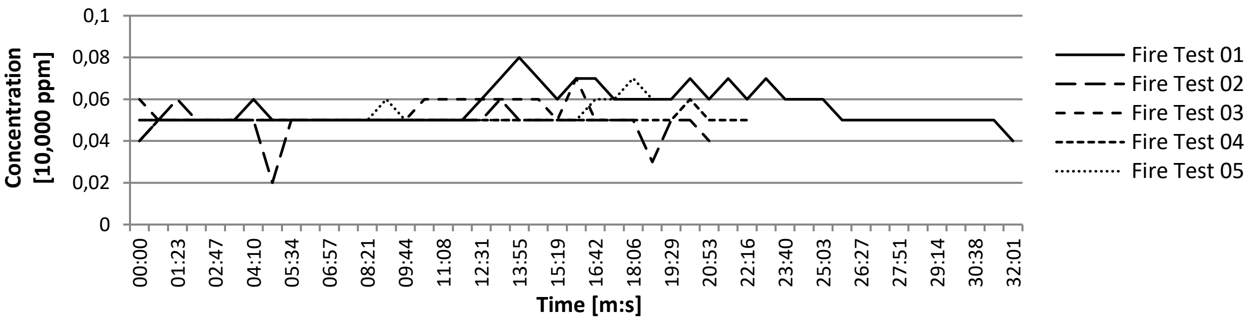



Figure 49 – $CO_2$ Concentration in Passenger Cabin during Fire Tests of Fire Scenario I

In conclusion the concentrations of toxic smoke gas components measured were not critical within fire tests performed. This shows that in case of an engine compartment fire in which a fire suppression system activates 1 min elapsed after ignition at the latest - whether it was completely successful or not - the passengers would not get exposed to critical concentrations of toxic smoke gas components for next minutes of evacuation.

In contrast to smoke the fire did not penetrate into the passenger compartment during the fire tests at all. It could be shown that within the time until activation of fire suppression, which in fire test was used for pre-burning and preheating, the fire was not penetrating into the passenger cabin.

In general a fire suppression system optimised for engine compartments of a bus and meeting the requirements of SP-Method 4912 would significantly minimise the hazard for passengers in case a bus fire starts in the engine compartment. However, fire suppression systems need prompt and reliable fire detection systems to get a valid signal for activating the fire suppression process. Therefore the quality and promptness of fire detectors were examined in these fire tests as well. In Table 23 an overview is given about the fire detectors tested. In total 16 fire detectors applying five different measuring principles were investigated during the engine compartment fires performed.

Table 23 – Fire Detectors Tested in the Bus Engine Compartment

| Fire Detectors tested in the Bus Engine compartment | | | | | | |
|---|---|---|---|---|---|---|
| | **Detectors** | | | | | |
| Method | Bimetallic spot thermal detectors (STD) | Discrete linear thermal detector (LTD) | | Averaging linear thermal detector (averaging LTD) | Optical detector (OD) | Smoke detector (SD) |
| | | Hydraulic | electrical | electrical | | |
| Quantity | 4 | 2 | 3 | 1 | 4 | 1 |
| Reusable | No | No | No | Yes | Yes | No |

Figure 50 shows the fire detectors examined and their location in the engine compartment. Several spot thermal detectors (STD) marked by green spots with No. 1 - 4, optical detectors (OD) highlighted by yellow spots with No. 1 - 4, one smoke detector (SD) given by a white spot with No. 0 and linear thermal detectors (LTD) were run concurrently during all the fire tests in the engine compartment. The LTD can be divided into hydraulic ones marked by blue spots with No. 1 - 2 and electrical ones highlighted by red spots with No. 1 - 2. Also an averaging linear thermal detector (Averaging LTD) given by a grey spot with No. 1 was tested.

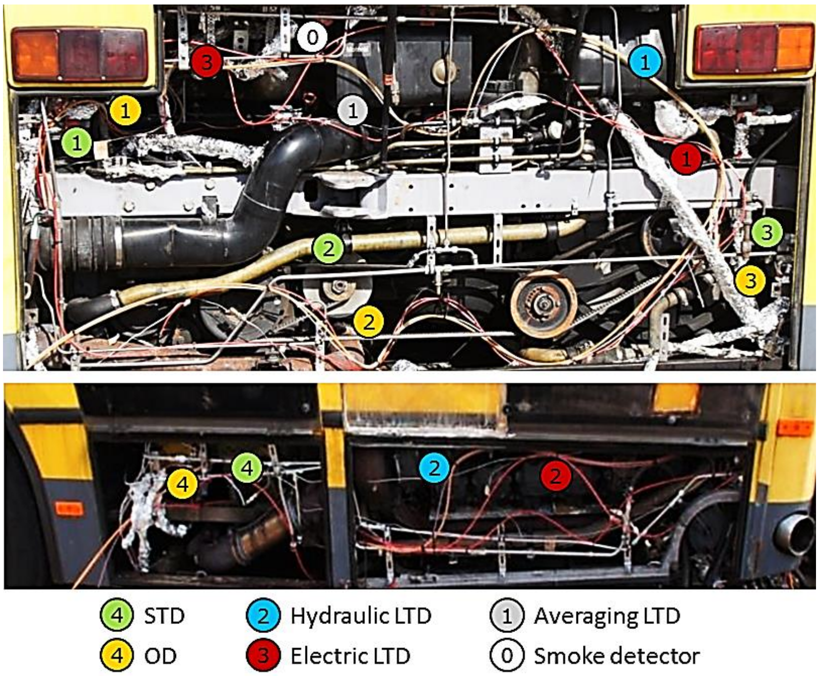



Figure 50 – Fire Detectors Tested and Their Locations in Engine Compartment

In Table 24 fire tests performed including their fire scenarios as well as their detection times determined are summarised. It must be considered that the measurements of detection time started already with the ignition of first fire source in the engine compartment. In case a detector did not give alarm within the pre-burn time the fire suppression was most likely the reason for no further detections.

In fire test 08 the fuel in one of the prepared pool fire pans got spilled during the igniting process. Thus, the detecting times of some fire detectors came to questionable results which might be skewed. Therefore the results of Fire test 08 were annulled afterwards.

STD and SD were used in fire scenario I since STD are currently applied in new buses almost exclusively although they don’t provide reliable results as seen in these tests. Furthermore, a smoke detector was installed in the engine compartment against its field of application to demonstrate that smoke detectors are expedient in engine compartments as well. The SD was discarded starting with fire test 03 since two incidences of false alarm occurred already in the first two fire tests while preheating. In all the other fire tests performed the complete set of fire detectors except smoke detectors were examined.

Table 24 – Fire Detection Times Measured

| Fire Detection Times Measured | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tests** | | | **Detectors in engine compartment** | | | | | | | | | | | | | |
| Fire test | Fire scenario | Pre-burn time | STD 1 | STD 2 | STD 3 | STD 4 | Hydraulic LTD 1 | Hydraulic LTD 2 | Electrical LTD 1 | Averaging LTD | OD 1 | OD 2 | OD 3 | OD 4 | SD 0 |
| 01 | I | 60 | no | - | - | - | - | - | - | - | - | - | - | - | fa |
| 02 | I | 60 | no | - | - | - | - | - | - | - | - | - | - | - | fa |
| 03 | I | 60 | no | - | - | - | - | - | - | - | - | - | - | - | - |
| 04 | I | 60 | no | - | - | - | - | - | - | - | - | - | - | - | - |
| 05 | I | 60 | no | - | - | - | - | - | - | - | - | - | - | - | - |
| 06 | II | 60 | no | no | no | no | 45 | 43 | 44 | 37 | 25 | 1 | no | no | - |
| 07 | II | 60 | no | no | no | no | 42 | 30 | 41 | 32 | 3 | 1 | no | no | - |
| 09 | III | 30 | no | no | no | no | - | - | 29 | 27 | no | no | no | 3 | - |
| 10 | III | 30 | no | no | no | no | - | 7 | 15 | 12 | no | no | no | 3 | - |
| 11 | III | 30 | no | no | no | no | 12 | 14 | 12 | 12 | no | no | 11 | 1 | - |
| 12 | IV | 10 | no | no | no | no | - | - | - | 7 | 8 | 10 | 1 | 5 | - |

Measurements times in [s]
’no‘ = no alarm
‘-‘ = not tested
’fa‘ = false alarm at preheating

In sum all STD did not detect any fire. Hydraulic and electrical LTD reliably detected all the fires run when at least 30 s were given for pre-burning. Due to just 10 s of pre-burn time till fire suppression activation in fire scenario IV the hydraulic and electrical LTD could not detect this fire. OD were able to detect fires just within few seconds, however, due to the overstuffed engine compartment obstructing the sensor view some of the fires remained undetected.

In conclusion LTD is highly recommended to be applied in such engine compartments. Furthermore STD and SD should be kept away from such engine compartments since they provided unreliable results. OD can provide extreme fast results, however, seems not be fitted in engine compartments since the optical sensor might be narrowed by either dirt or debris or just by the poor visibility available in engine compartments.

### 3.2.4 Bus Passenger Compartment

In addition to fire tests run in the engine compartment smoke tests were conducted in the passenger compartment as well since material tests performed in the SDC already proved that most bus interior materials generate extreme amounts of opaque and toxic smoke as summarised in Table 15 and 16. Based on these results the spread of smoke within the passenger compartment of the test bus was investigated. In particular four smoke scenarios based on different smoke sources combined with several ventilation conditions were conducted as summarised in Table 25.

Table 25 – Smoke Sources and Scenarios

| Smoke Sources and Scenarios | | | |
|---|---|---|---|
| **Smoke scenario** | **Simulation of** | **Fire source** | **Smoke conditions** |
| I | Local ignition of interior part or hand baggage | 100 g PU foam block in the back of the passenger cabin | Hot and opaque |
| II | Smouldering of electronic parts | smoke cartridges in the back of the passenger cabin | Warm and white |
| III | Arson I | Paper pillow on passenger seat | Hot and opaque |
| IV | Arson II | Paper drenched with gasoline on passenger seat | Extremely hot and opaque |

For smoke scenario I polyurethane (PU) foam was chosen to be source of smoke as shown in Figure 51 on the left. In particular foam blocks limited to 100 g portions were ignited by a lighter since it generates high amounts of hot and opaque smoke as available in real fires only.

For smoke scenario II a smoke cartridge from the manufacturer NO CLIMB was applied which produces white smoke. Its smoke behaviour resembles to smouldering as shown in Figure 51 on the right and in comparison to burning PU foam the smoke cartridges do not leave residues on interior surfaces affected by smoke wherefore manufacturing facilities predominantly use such cartridges for internal smoke tests instead of real fires.

The fire sources of smoke scenario I and II were applied in a fire bowl located in the back of the bus gangway to provide a smoke source nearby the engine compartment to simulate smoke penetration from an engine compartment fire.

Figure 51 – Sources of Smoke Scenario I (both left) and Smoke Scenario II (both right)

In addition to smoke scenario I and II in which external fire sources were used to generate smoke the smoke scenario III and IV were based on burning passenger seats. To simulate arson attacks the passenger seats were ignited by newspaper build up to a standardised paper pillow according to DIN 5510 described in Chapter 3.2.1 as shown in Figure 52 on both left pictures. In contrast to smoke scenario III the paper pillow used was additionally drenched with 0.2 l gasoline for smoke scenario IV in order to simulate a harder arson attack as shown in Figure 52 on both right pictures.

Figure 52 – Sources of Smoke Scenario III (both left) and Smoke Scenario IV (both right)

During smoke tests performed several ventilation conditions focusing at different combinations of opened or closed trap windows and ventilation flaps were applied. Table 26 summarises the different ventilation conditions of smoke tests conducted.

Table 26 – Ventilation Conditions while Smoke Tests

| Ventilation Conditions while Smoke Tests | | | | |
|---|---|---|---|---|
| **Smoke test** | **Smoke scenario** | **Doors** | **Air skylight** | **Trap windows** |
| 1 | I | Closed | closed | closed |
| 2 | II | Closed | closed | closed |
| 3 | I | Closed | closed | opened |
| 4 | II | Closed | closed | opened |
| 5 | I | Closed | opened | closed |
| 6 | II | Closed | opened | closed |
| 7 | III | Closed | closed | closed |
| 8 | III | Closed | closed | closed |
| 9 | IV | Closed | closed | Closed |

For determining detection times several smoke detectors were installed in the test bus as shown in Figure 53. They were basically developed for the application in rail vehicles and conform to ARGE Guidelines requirements [62]. Smoke detectors specialised for conditions and requirements of road vehicles only were not available on the market.

Figure 53 – Hekatron ORS 142 Rail and Firedect S65

Locations of smoke detectors summarised in Table 27 were chosen based on two different approaches. On one side hot smoke rises principally quickly up to the ceiling. Therefore the ceiling got smoke detectors in the front (SD1), middle (SD2) and back (SD3) of the passenger compartment in order to analyse the smoke spreading along it. On the other side smoke can easily penetrate through maintenance flaps into the passenger cabin which suggests that smoke detectors are to be installed adjacent to them (SD 4 and 5). In addition also some thermocouples and cameras were used to monitor the fire and smoke propagation during the smoke tests. Their locations are shown in Figure 43.

Table 27 – Smoke Detectors installed in Passenger Compartment

| Smoke Detectors installed in the Passenger Compartment | | | |
|---|---|---|---|
| **No.** | **Manufacturer** | **Type** | **Position** |
| SD 1 | Hekatron | ORS 142 rail | Front ceiling area |
| SD 2 | Hekatron | ORS 142 rail | Middle ceiling area |
| SD 3 | Hekatron | ORS 142 rail | Back ceiling area |
| SD 4 | Firedect | S65 | Second last seat row at the left side panel, at knee-height, nearby the maintenance flaps to the engine compartment |
| SD 5 | Firedect | S65 | Under the last seat row at the side panel of the gangway beside the last door |

Smoke detection times measured during smoke tests are summarised in Table 28. In conclusion the differences between hot smoke in smoke scenario I and just warm smoke in smoke scenario II were reflected in detection time as well. Especially the smoke propagation along the ceiling from SD 3 in the back to SD 1 in the front proved that hot smoke propagates much faster than warm smoke. In contrast warm smoke spread more equally distributed in all directions starting from source of smoke. This fact was also verified by smoke test measurements since SD 4 and SD 5 detected smoke only while tests based on smoke scenario II in which cartridges were applied for generating smoke.

In conclusion smoke was always detected within 1 min in each smoke scenario. When focusing on smoke sources, the smoke generated by PU foam was detected faster than smoke generated by cartridges while smoke generated by the ignited passenger seats was faster one more. In total smoke scenario IV caused the fastest smoke detection time.

Table 28 – Smoke Detection Times

| Smoke Detection Times | | | | | | |
|---|---|---|---|---|---|---|
| **Smoke Test** | **Smoke Scenario** | **Detection times [s]** | | | | |
| | | **SD 1** | **SD 2** | **SD 3** | **SD 4** | **SD 5** |
| 1 | I | 69 | 47 | 43 | not | not |
| 2 | II | 217 | 81 | 54 | 121 | 234 |
| 3 | I | 84 | 53 | 47 | not | not |
| 4 | II | 232 | 87 | 52 | 187 | 226 |
| 5 | I | 103 | 54 | 39 | not | not |
| 6 | II | 254 | 92 | 46 | 241 | 193 |
| 7 | III | 61 | 37 | 48 | 107 | 145 |
| 8 | III | 64 | 43 | 42 | 98 | 152 |
| 9 | IV | 52 | 33 | 37 | 72 | 87 |

Beside smoke detection times, smoke test 1 and 2 showed that the complete passenger compartment was quickly filled with opaque smoke as shown in Figure 54 since air skylights, doors and windows were kept closed. In contrast to these smoke tests conducted in an almost sealed passenger cabin implementing small openings could prevent the passenger compartment from getting filled completely with smoke. In particular a trap window opened as applied in smoke test 3 and 4 or even an opened air skylight as used in smoke test 5 and 6 brought this result since such openings work like exhausts through which the smoke streams out of the passenger cabin while the space below this opening level always remains almost free of smoke as shown in Figure 55. The hotter the smoke the better this effect could be observed as shown in Figure 56.


Figure 54 – Smoke Test 1 (left picture) and 2 (right picture)

Figure 55 – Smoke Test 3 (left picture) and 4 (right picture)

Figure 56 – Smoke Test 5 (left picture) and 6 (right picture)

Smoke tests 7 and 8 showed that the scenarios simulating arson attacks generate very hot smoke. This was also reflected by very fast detection times measured. In these tests the smoke was so hot that the window nearby the ignited passenger seat burst as shown in Figure 57 and the ceiling above was deformed significantly afterwards.

Figure 57 – Smoke Test 7 (left picture) and 8 (right picture)

Smoke test 9 was performed to finally present a very severe arson attack scenario as shown in Figure 58 in which the newspaper placed on a passenger seat was additionally drenched with gasoline before getting ignited. This generated extremely hot smoke reflected by very fast detection times.


Figure 58 – Smoke Test 9

In summary any opening, whether caused by an air skylight raised, a window tilted or a door opened, will prevent the bus from getting filled with smoke very efficiently since the hot smoke only fills the cabin from the ceiling down to the level of the highest opening where the smoke streams out of the vehicle. Thus, there remains a potentially much bigger smoke-free range for the passengers to escape the bus safer.

# 4. Numerical Simulations

This chapter shows how numerical simulations based on Computational Fluid Dynamics (CFD) can be applied on road vehicles in order to estimate their fire behaviour predominantly regarding fire and smoke propagation and how to simulate bus fire scenarios realistically.

## 4.1 Modelling

Fire scenario modelling is an essential step in preparing numerical fire simulations, in which the environment as well as the boundary conditions will be defined. Previously adequate CFD software for fire simulations needs to be established from several commercial and research software available on the market. Table 29 shows the most common ones together with their related discretisation properties and their sub models for turbulence, radiation and combustion. For numerical simulations in the dissertation at hand the Fire Dynamic Simulator (FDS, Version 5.5) was chosen since it is available as freeware.

Table 29 – Common CFD Fire Simulation Software [12]

| Common CFD Fire Simulating Software | | | | | |
|---|---|---|---|---|---|
| | Numeric approach | Turbulence model | Radiation model | Combustion model | Discretisation |
| **ANSYS CFX** | Finite-volume-method | LES/ RANS/ SST | P1/ Rossland/ DO/ DTM | Finite Rate/ Eddy break-up/ mixture fraction | Structured/ unstructured, adaptive, rectangular, cylindrical |
| **ANSYS FLUENT** | Finite-volume-method | LES/ RANS/ SST | P1/ Rossland/ DO/ DTM | Finite Rate/ Eddy break-up/ mixture fraction | Structured/ unstructured, adaptive, rectangular, cylindrical |
| **Open FOAM** | Finite-volume-method | LES/ RANS/ SST | DO/ DTM | Finite Rate/ Eddy break-up/ mixture fraction | Structured/ unstructured, adaptive, rectangular, cylindrical |
| **FDS** | Finite-difference-method | LES | DTM | Mixture fraction | Structured, rectangular |

### 4.1.1 Fire Dynamic Simulator

FDS is an established open source CFD software developed by the USA Building and Fire Research Laboratory at the National Institute for Standardisation (NIST) for estimating fire behaviour in buildings. In a modelled 3D environment FDS can calculate fire-driven fluid flows by solving numerically the Smagorinsky form of the Large Eddy Simulation technique (LES) which is a mathematical turbulence modelling approach adopting Navier-Stokes equations. Predominantly FDS is used for low-speed and thermally-driven fluid flows, which are focused on heat and smoke transport caused by fires. [Compare with 63 and 64]

Generally FDS is a field model which is based on the finite difference method (second order accurate in space and time). Its discretisation is based on a rectangular grid. All objects included need to be integrated into the basic cell grid adopted. Main features of the Fire Dynamic Simulator concerning fire modelling are the sub models for involving combustion, heat radiation and flow turbulence. The combustion model is based on the mixture fraction approach. In detail the mixture fraction is a scalar quantity defined as a fraction of gas at a point in the flow field that originates from fuel. This approach also includes heat and smoke production due to the combustion reaction. Principally the mixture fraction combustion approach assumes infinitely fast combustion reactions and controlled mixing of fuel and oxygen in the combustion processes. As an essential input for gas phase modelling the rates of reactants and products need to be established for the chemical reaction equation shown in (4.1). [Compare with 63 and 64]

$$C_xH_yO_zN_vOther_w + v_{O_2}O_2 \rightarrow v_{CO_2}CO_2 + v_{H_2O}\,H_2O + v_{CO}CO + v_{Soot}Soot + v_{N_2}\,N_2 + v_{H_2}\,H_2 + v_{Other}Other \qquad (4.1)$$

For combustible solids and liquids a pyrolysis sub model is also included in FDS. This pyrolysis model is based on the solution of an one-dimensional heat transfer equation and can be applied on boundary surfaces of the flow field. [Compare with 63]

In a submodel of the pyrolysis model the material surface can be composed of different layers consisting of diverse components. In solids the heat transfer is calculated by using a function which incorporates the composition of material layers and their thermal properties. Fundamentally reaction products are differentiated in water vapour, fuel and residues. Water vapour and fuel are immediately absorbed by adjacent cells of flow field when getting produced. Residues remain in its initial solid. [Compare with 63 and 64]

The Fire Dynamic Simulator contains also a sub model for radiative heat transfer for which mainly the solution of the radiation transport equation for grey gases makes allowance for. Grey gases mean the fluid which is irradiated by heat radiation and in which (independently from the related wavelength) emission and absorption of radiation occurs [Compare with 65]. The radiation transport equation is based on a method similar to the Finite Volume Method (FVM), in which the same grid as applied for the flow computations is used [64]. In few cases a supplemented wide band mode will be used as well [Compare with 65].

For the integration of fire detectors and fire suppression systems separate functions representing thermocouples as shown in Figure 59 on the left, smoke detectors as shown in Figure 59 in the middle and a sprinkler system as shown in Figure 59 on the right are available in FDS as well.

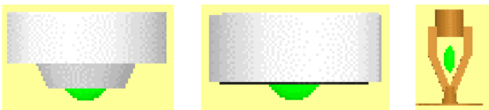


Figure 59 – FDS Thermocouple, Smoke Detector and Sprinkler [64]

For creating a numerical FDS simulation principally a FDS input file shall be written in an editor software as e.g. Notepad. With command lines all aspects of the subsequent simulation, such as the geometries, the boundary conditions and the fire scenario, need to be predefined in the FDS input file. The general structure of a FDS input file is shown in Annex V.

For integrating complex geometries, as for instance a bus model with its complete interior, additional software supports and simplifies the preparation of FDS input files. For the dissertation at hand Pyrosim 2010 [66] was used which mainly is a graphical user interface for the Fire Dynamic Simulator. In addition a free post processing software from NIST developed for evaluation of FDS simulations and named ‘Smokeview’ was applied to visualise the FDS simulations run [64].

Both, the Fire Dynamic Simulator and the Smokeview software, has been originally developed for the application in civil engineering [63 and 64]. As shown in the dissertation at hand, FDS can also be applied in other fields of fire safety engineering. However, simulating with the Fire Dynamic Simulator is a very time-consuming approach even if less than other CFD programmes. On a personal computer such a half-hourly bus fire simulation with a mesh of about one million cells took about 4 weeks. Nevertheless it could be shown that FDS simulations can obtain suitable results.

### 4.1.2 Bus Models

Different bus models were used for simulating bus fires. This can be seen as subsequent development steps in an enhancement process related to the features implemented and the level of detailed design. Therefore three coaches and a city bus were modelled intending to reproduce different fire scenarios.

#### 4.1.2.1 Initial Bus Model

In the beginning a simplified bus model from a student research project executed at BAM [67] was adopted which originally was used in order to check if it was possible to simulate the severe 2008 Hanover bus fire. This bus fire was the worst one ever occurred in Germany and caused twenty fatalities. The bus affected was a 2003 Mercedes-Benz O 350 measuring 12.00 m in length, 2.55 m in width and 3.90 m in height. In this bus model some simplifications were implemented which neglect the influence of fuel, tires, luggage and engine compartment as shown in Figure 60. Also luggage and clothing in the passenger compartment were left out in the model. This was done in order to focus on fire behaviour entailed by interior parts only since passenger seats, dashboard and luggage racks above passenger seats are the components which mainly influence the fire development in such a bus. Ventilation was not implemented and all other parts were neglected or had been set incombustible in this first model.

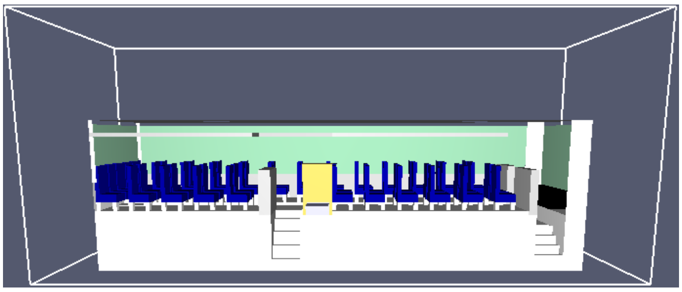


Figure 60 – Initial Bus Model Representing a Mercedes-Benz O 350 SHD [67]

Regarding discretisation a 10 cm cubical cell grid was applied which splits the initial bus model into 120 cells in length, 26 cells in width and 40 cells in height and which contains 124,800 cells in total. To simulate the bus model more accurately, 1 m empty space was added around and over the bus body contour. Therefore the complete bus model amounts to 140 cells in length, 46 cells in with and 50 cells in height making 322,000 cells in total.

Functions for doors getting opened and windows getting destroyed are also implemented in this bus model applying the FDS object removal feature. Doors are getting deactivated at a predefined point in time. In contrast windows are connected to thermocouples which trigger the removal function when exceeding a predefined temperature level at the correlated window surface.

#### 4.1.2.2 Hanover Bus Fire Model

The Hanover bus fire model exactly conforms to the 2003 Mercedes-Benz O 350 shown in Figure 61 on the right which was the type of bus destroyed in the 2008 Hanover bus fire. The model was set up based on a detailed CAD model shown in Figure 61 on the left which was downloaded as freeware from a computer game forum in the internet [68]. It was completed with lavatory, galley and stairs. Modelling and simulating the Hanover bus fire with this bus model was part of a diploma thesis at BAM [69] in which the fire safety performance of different interior material requirements applied in the coach was established. This was generally done in parallel to the bus model of a 2012 Coach introduced next.

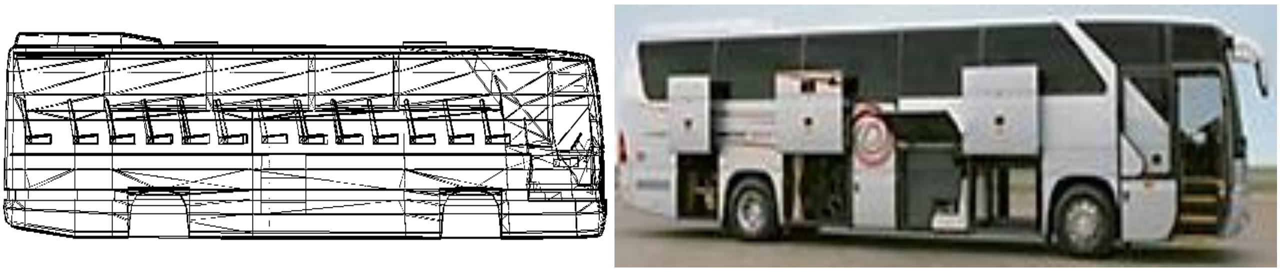


Figure 61 – CAD Model of a Mercedes-Benz O 350 SHD and its Original [69]

For compiling the bus model with FDS it got 1 m empty space around and over the bus body and was afterwards attuned to a cubical 10 cm cell grid. Thus, the Hanover bus fire model features the same cell grid as the initial bus model which also contains 322,000 cells in total resulting from its dimensions by 140 cells in length, 46 cells in width and 50 cells in height.

Since the official survey report of the 2008 Hanover bus fire [70] was available in which a break in a cable located in the cable duct between lavatory and galley had been established as the initial fire source, further details were included in this bus model, such as cable ducts or suitcases in the luggage compartment. Figure 62 shows the comparison between the Hanover bus model and the wrack of the Hanover bus fire.

Figure 62 – Hanover Bus Fire Model [69] and Wrack of Hanover Bus Fire [70, 71]

Functions for doors getting opened and windows getting destroyed were adopted from the initial bus model. In order to enhance this bus model to real driving conditions, a FDS fan function for simulating 80 km/ h airstream was implemented affront the bus [69]. But unrealistically this simulation caused inexplicable air movements inside the bus although all openings outwards remained closed and all fans inside shut off. This proves that the integration of airstream simulating driving does not work in FDS.

#### 4.1.2.3 Bus Model of a 2012 Coach

To investigate an actual coach a third bus model was set up on a very detailed CAD model of a 2012 Mercedes-Benz O 350 Tourismo 2 as shown in Figure 63 which was downloaded as freeware from a computer game forum in the internet [68]. In contrast to both earlier bus models the lavatory is positioned between rear stairs and rear wheel house on the right side.

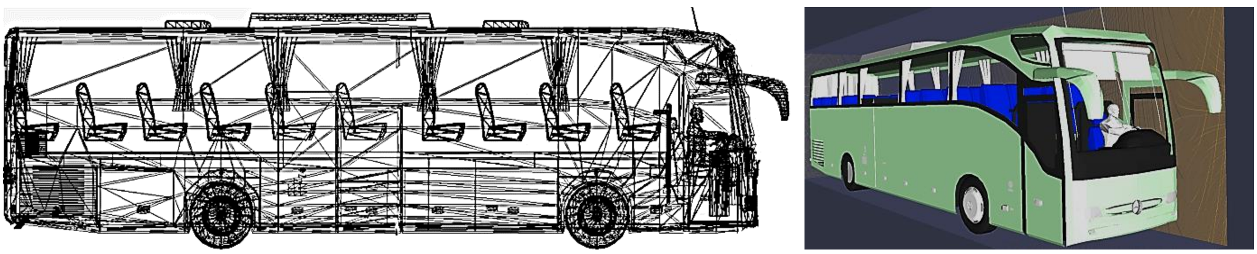


Figure 63 – CAD Bus Model of a 2012 Mercedes-Benz O 350 Tourismo 2

As a result of a bus manufacturer visit detailed information about the ventilation concept could be gathered and was implemented in the bus model accordingly. Thus, the bus model was enhanced by the latest ventilation concept installed in the original 2012 Mercedes-Benz O 350 Tourismo 2. Fresh air is let in above each passenger seat by fan nozzles which entail a light overpressure in the passenger cabin. At the same time due to driving a low pressure exits at an air outlet pointing towards the street which is located in the front of the luggage compartment. The difference in pressure entails an air flow from passenger cabin through gangway bottom louvers into the luggage compartment and along the underfloor to the front area.

The first step was to implement the air inflow by nozzles above passenger seats based on the FDS fan functions. Since flow speed data measured in the original coach were not available, the air flow rate had to be assumed. For this several flow rates were simulated and evaluated as an inlet flow rate set to 0.5 m³/s shown in Figure 64 on the left and set to 1 m³/s shown in Figure 64 on the right.

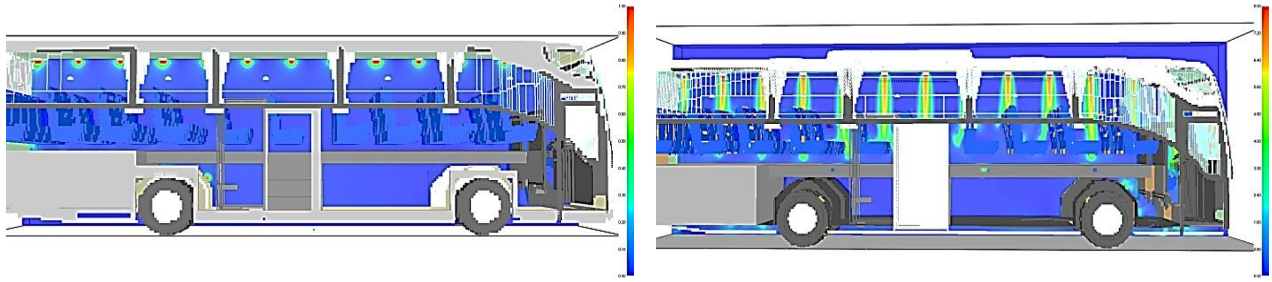


Figure 64 – Air Inlet with Flow Rate of 0.5 m/s (left) and 1 m/s (right) in 2012 Coach Model

Since simulations investigating ventilation within the complex bus model would each entail at least several weeks computer running time, the ventilation had been pre-simulated within a simplified model based on main ventilation items only. This auxiliary model contained two compartments, one superimposed on the other, which were connected by a couple of small link openings. The upper compartment was added by air inlets at the ceiling and the underfloor compartment was complemented by an outlet accordingly to the detailed bus model as shown in Figure 65.

Both flow rates previously run generate overpressure in the passenger compartment pushing permanently the air through louvers into the luggage compartment. Thus an average airflow of 0.8 m/s was chosen to simulate. Air jets at the gangway bottom louvers are visible in in Figure 65 on the left. In the simplified model those effects can be indicated even more easily by the light blue air jets shown in Figure 65 on the right. The same applies also for the air jet at the front outlet towards the ambient air.

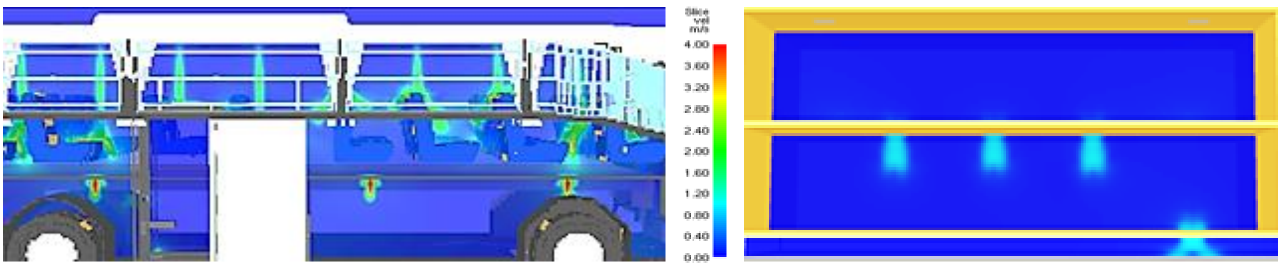



Figure 65 – Ventilation Comparison between 2012 Coach Model and its simplified Fire Model

The effects that fire developed hidden in the luggage compartment and no passenger recognised any smoke can also be gathered from the official survey report of the 2008 Hanover bus fire [70]. The most likely explanation for this is that due to the overpressure in the passenger cabin the smoke was entirely kept in the luggage compartment. Figure 66 shows this effect at 10 s elapsed on the left and at 40 s elapsed on the right. All this proves that implementing an original coach ventilation concept in FDS bus models is feasible despite its complexity.

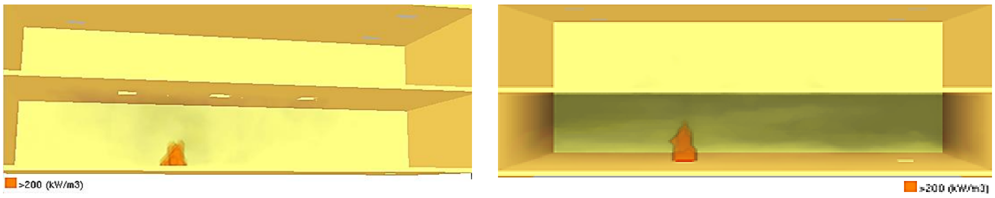


Figure 66 – Simulation of Smoke kept in Luggage Compartment

Regarding discretisation a 5 cm cubical cell grid was applied which splits the Bus Model of a 2012 Coach into 240 cells in length, 51 cells in with and 78 cells in height. Thus, in total the bus model contains 954,720 cells. To simulate the bus model more accurately, empty space was added around and over the bus body contour. Therefore the complete bus model amounts to 284 cells in length, 72 cells in with and 87 cells in height which makes 1,778,976 cells in total. Functions for doors getting opened and windows getting destroyed were taken over from earlier bus models.

#### 4.1.2.4 City Bus Model

A fourth bus model representing a city bus was prepared since a video of a city bus fire was available showing a city bus while burning completely off. Figure 67 shows a video snapshot of this very city bus fire versus the city bus model.

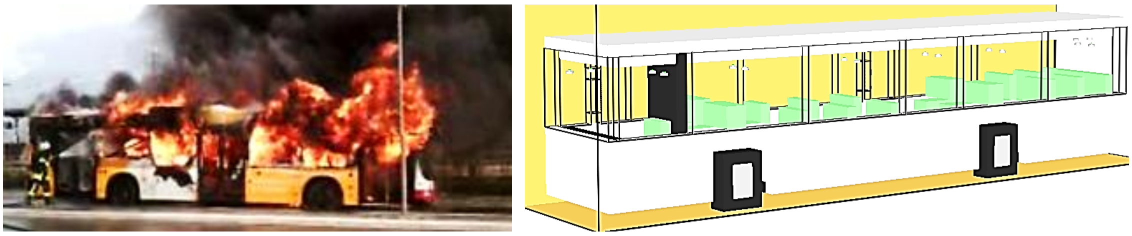


Figure 67 – Real City Bus Fire [71] versus City Bus Model

In comparison between city buses and coaches the formers have a less complex interior design and lower level of comfort. This fact also entails a generally lower fire load in city buses due to less passenger seats and interior parts implemented.

Implementing ventilation in the city bus model is not easy since in real operation conditions a city bus opens the doors for alighting and boarding of passengers every few minutes. This leads to frequent exchange of air and therefore the ventilation is usually set off. Thus, the ventilation aspect is neglected in the City Bus Model. But nevertheless, in case of fire a strong overpressure builds up in the passenger compartment pushing the smoke through the door sealing as shown in Figure 68 on the left [71]. To simulate this effect the city bus model got three small openings between the bi-parting door leaves as shown in Figure 68 on the right. Functions for doors getting opened and windows getting destroyed were taken over from earlier bus models as well.

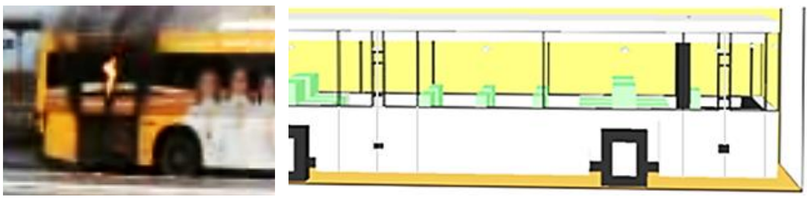


Figure 68 – Implementation of leaking Door Seal seen in Bus Fire [71]

Regarding discretisation a 10 cm cubical cell grid was applied which splits the bus model into 120 cells in length, 26 cells in with and 30 cells in height. Thus, in total the bus model contains 93,600 cells. To simulate the bus model more accurately and to consider the narrow parking condition city buses are usually parked in depots, an empty space range of 0.4 m was added around the bus body. Over the bus 1 m empty space was set. Thus, the complete bus model amounts to 128 cells in length, 34 cells in width and 50 cells in height. This makes 174,080 cells in total.

### 4.1.3 Material Parameters

For preparing fire simulations material parameters are essentially needed to complete the model to simulate. Material data of typical bus materials were already established while examining their fire behaviour in fire tests as described in Chapter 3. However, using raw material data from corresponding fire tests only are not expedient for fire simulations. Before implementing those in a fire model they need to be verified by simple simulations in order to adjust them to the characteristics fitting best to the simulation software used. The reason is that each simulation is a simplification of reality and requires neglecting individual issues, such as e.g. the inertia phenomena.

#### 4.1.3.1 Passenger Seats

Passenger seats represent the highest number of bigger interior parts of a bus and usually contain a significant portion of fire load resulting almost completely from the upholstery applied. Therefore, the passenger seats were particularly focused at. First material data gained in a student research project executed at BAM [67] were used as basic for investigations and is called ‘PU Foam Basic’ in the dissertation at hand. In further steps the PU Foam Basic was adjusted to the fire behaviour seen in fire tests with bus passenger seats. This was done within separate fire simulations in which the FDS material parameters were calibrated to the heat release measured in Chapter 3.2.1.

Since passenger seat tests were initiated by igniting a paper pillow the heat release portion of a single paper pillow was determined separately as mentioned in Chapter 3.2.1. For simulating the passenger seat test the heat release of such a paper pillow was modelled in FDS as well. In particular the ramp-up function for HRRPUA available in FDS was applied and its peak was set to 12 kW at 33 s and the end of ramp-down at 120 s. In Figure 69 the heat release rates of such a paper pillow measured in SBI, modelled and simulated in FDS are shown. When comparing the SBI curve measured and the FDS curve simulated especially the first increase of heat release is simulated very accurate.

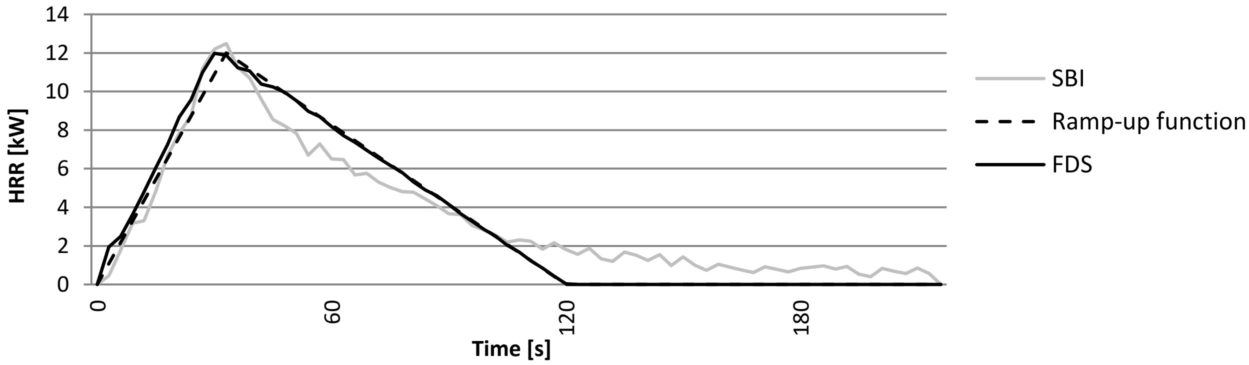



Figure 69 – Heat Release of a single Paper Cushion Measured and Simulated

Figure 70 shows different approaches for implementing the paper pillow as ignition source in FDS. In case of position A and B the heat release source represents a burning paper pillow in form of a rectangular solid conforming to the dimensions of the paper pillow. Position A is completely placed on seating and backrest surfaces which entails that only four sides of the paper pillow are able to release heat. Thus, the HRRPUA was set to 58.70 kW/m² according to the exposed surface of 0.21 m² to reach the peak HRR of 12 kW. In contrast position B features a paper pillow slightly shifted and lifted in order to obtain small distances towards seating and backrest surfaces. Thus, all sides of the paper pillow are contributing to the heat release. The HRRPUA of position B amounts to 32.68 kW/m² according to the exposed surface of 0.37 m² to reach the peak HRR of 12 kW. In case of position C and D the heat source is placed on the seat surface to simulate the paper pillow reflection on seating and backrest surfaces. The HRRPUA of position C was set to 75.19 kW/m² due to an exposed heat releasing surface of 0.16 m² for reaching the peak HRR of 12 kW. In case of position D the reflection was implemented as chessboard pattern in the surface layer of the seating and backrest. In particular this was done in order to increase the impact heat release acting for ignition. Since the surface for releasing heat was halved compared to the reflection area of position C due to the chessboard pattern applied, the HRRPUA was needed to double to get the 12 kW peak.

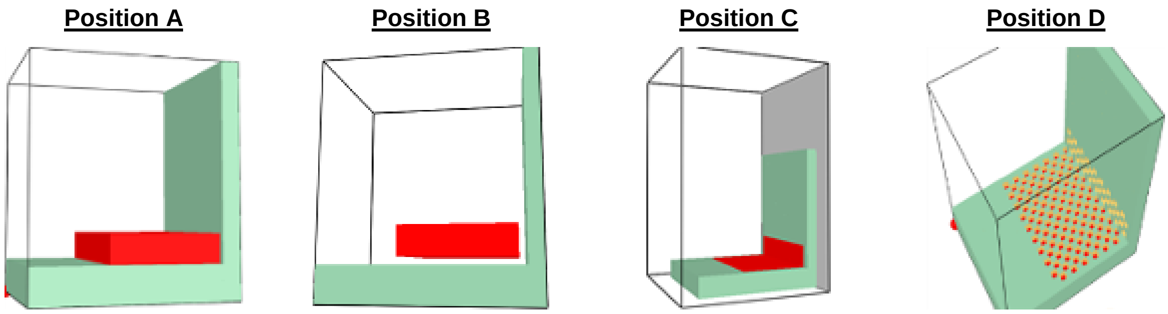



Figure 70 – Investigations on Implementing Paper Cushion on Passenger Seats

In conclusion to these investigations for simulating the ignition of passenger seats, only the position A delivered results as obtained from fire tests.

For adjusting the material parameter of polyurethane foam from passenger seat upholsteries to HRR values measured (see Chapter 3.2.1), the impact of each single material parameter in FDS was investigated.

The density determines mainly the period length of the HRR peak level. The higher the density is set the longer the peak level extends as shown in Figure 71.

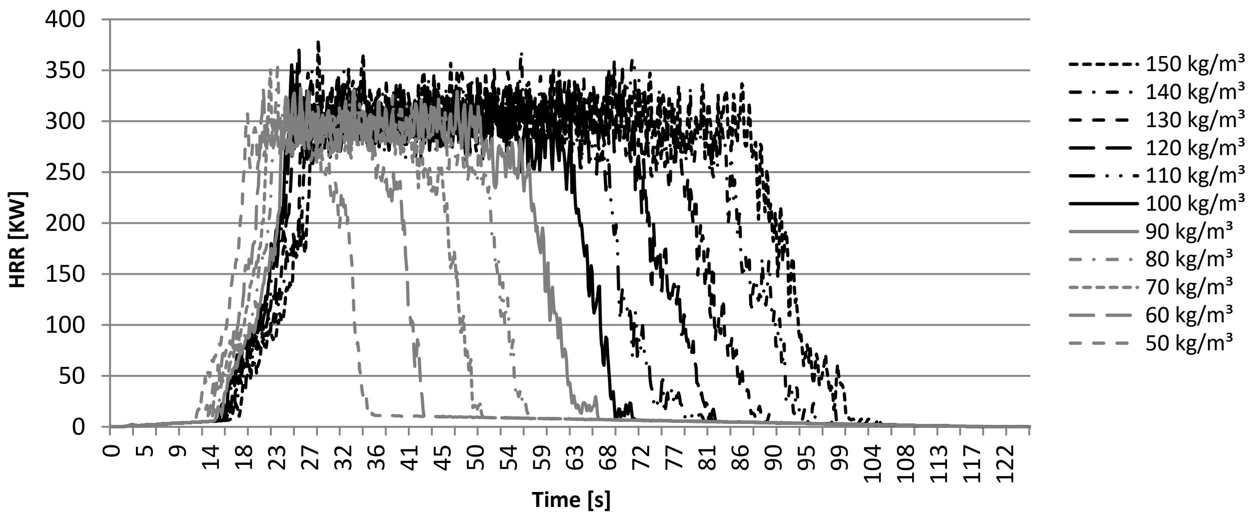



Figure 71 – Influence of Density Parameter in FDS Simulations

The specific heat mainly influences the HRR gradient after ignition and also slightly the point of ignition as shown in Figure 72. The lower the specific heat is set the steeper is the HRR gradient emerging after ignition and also the higher is the peak of HRR.

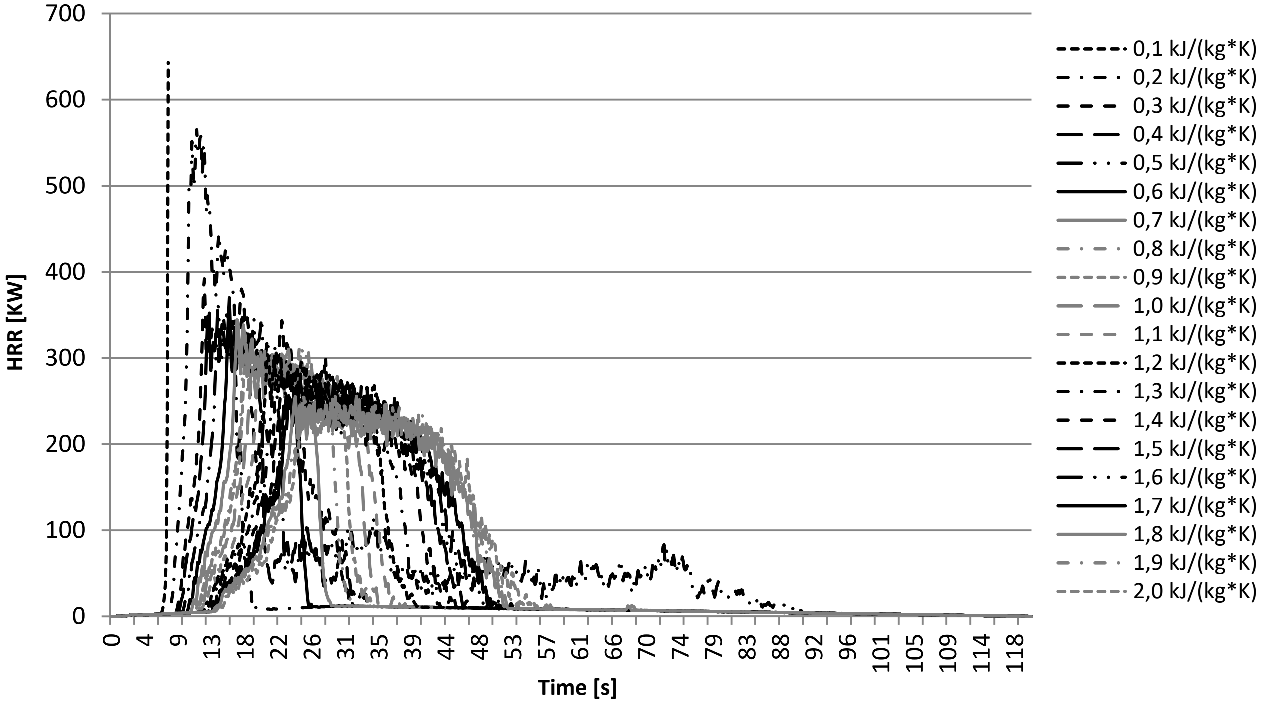



Figure 72 – Influence of Specific Heat Parameter in FDS Simulations

The lower the conductivity is set the sooner the material ignites and the steeper is the HRR gradient emerging after ignition as shown in Figure 73.

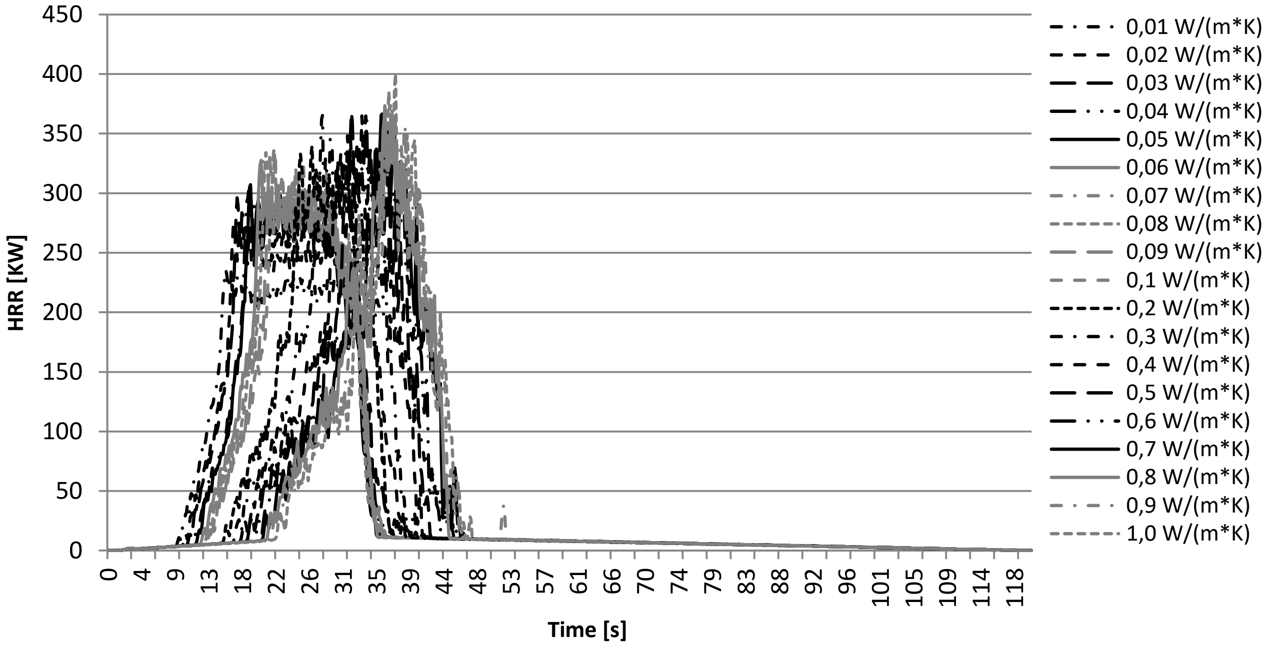



Figure 73 – Influence of Conductivity Parameter in FDS Simulations

Emissivity affects predominantly the HRR gradient after ignition and the peak level. The higher its emissivity is set the steeper is the gradient emerging after ignition and the higher is the HRR peak as shown in Figure 74. In all cases the ignition point in time will remain almost the same.

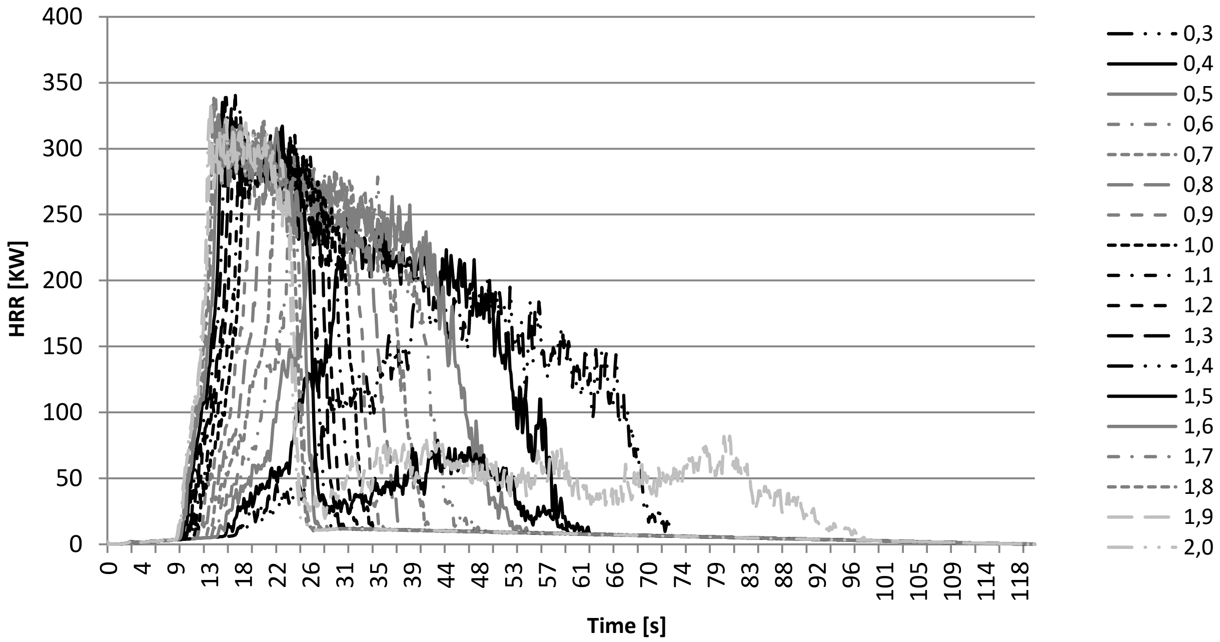



Figure 74 – Influence of Emissivity Parameter in FDS Simulations

Heat of combustion predominantly affects the HRR peak level while burning over an almost constant period of time as shown in Figure 75. The higher the heat of combustion is set the higher is the HRR peak level reached. Simulations with a value over 5000 kJ/kg have led to numerically instability in FDS.

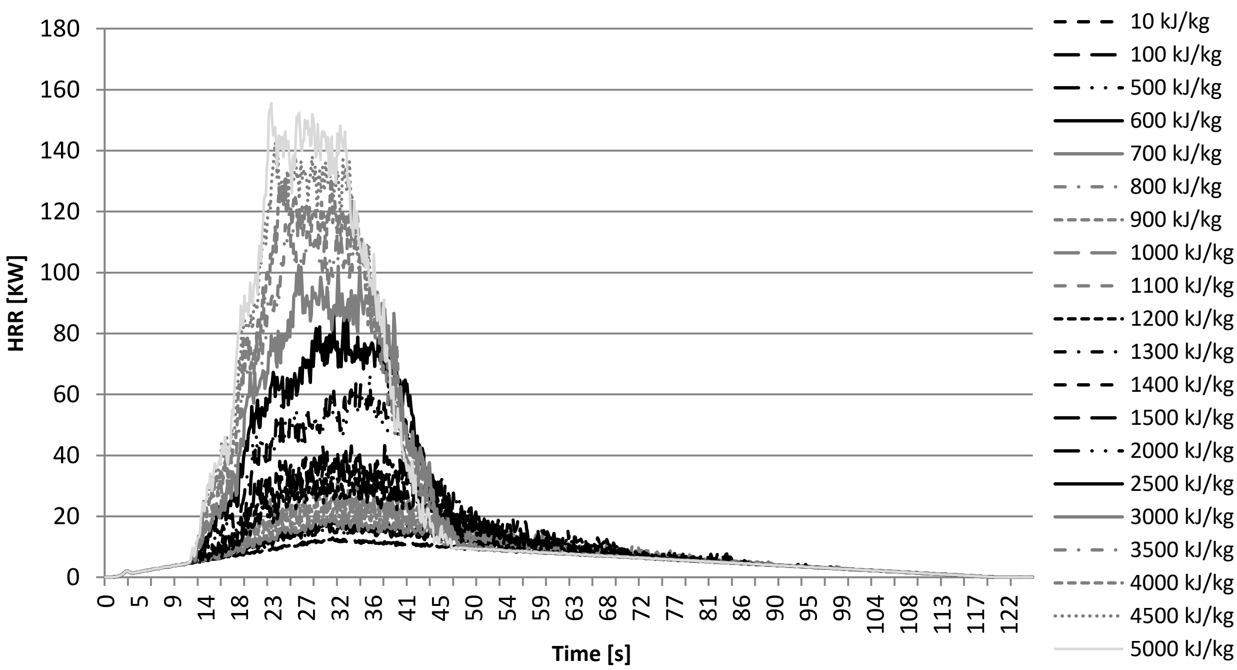



Figure 75 – Influence of Heat of Combustion Parameter in FDS Simulations

The absorption coefficient influences mainly the HRR gradient emerging after ignition and also slightly the ignition point in time. The higher the absorption coefficient is set the steeper is the HRR gradient and also the shorter is the total period of burning as shown in Figure 76.

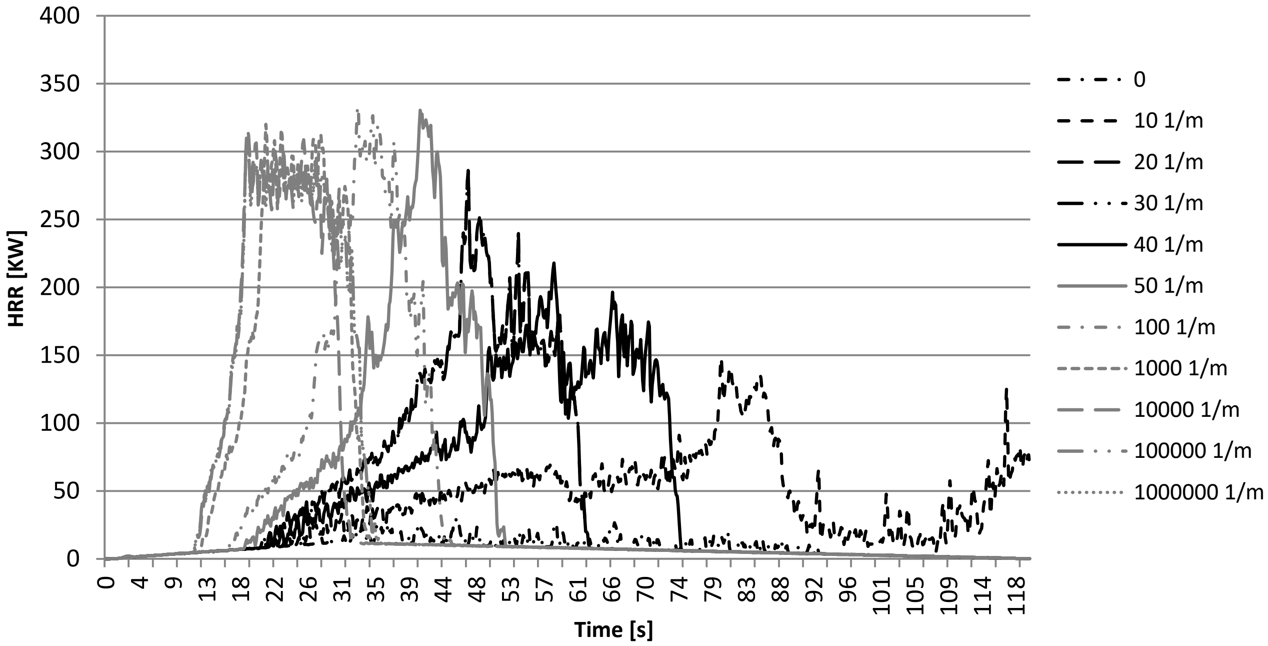



Figure 76 – Influence of Absorption Coefficient Parameter in FDS Simulations

In addition to main parameters of material properties also pyrolysis parameters were investigated in simulations. Figure 77 shows that the reference temperature does not affect the simulation that much as assumed. Values lower than 100°C lead to shorter periods of burning and to extremely high HRR peaks. However, the higher the reference temperature is set the lower is the HRR peak.

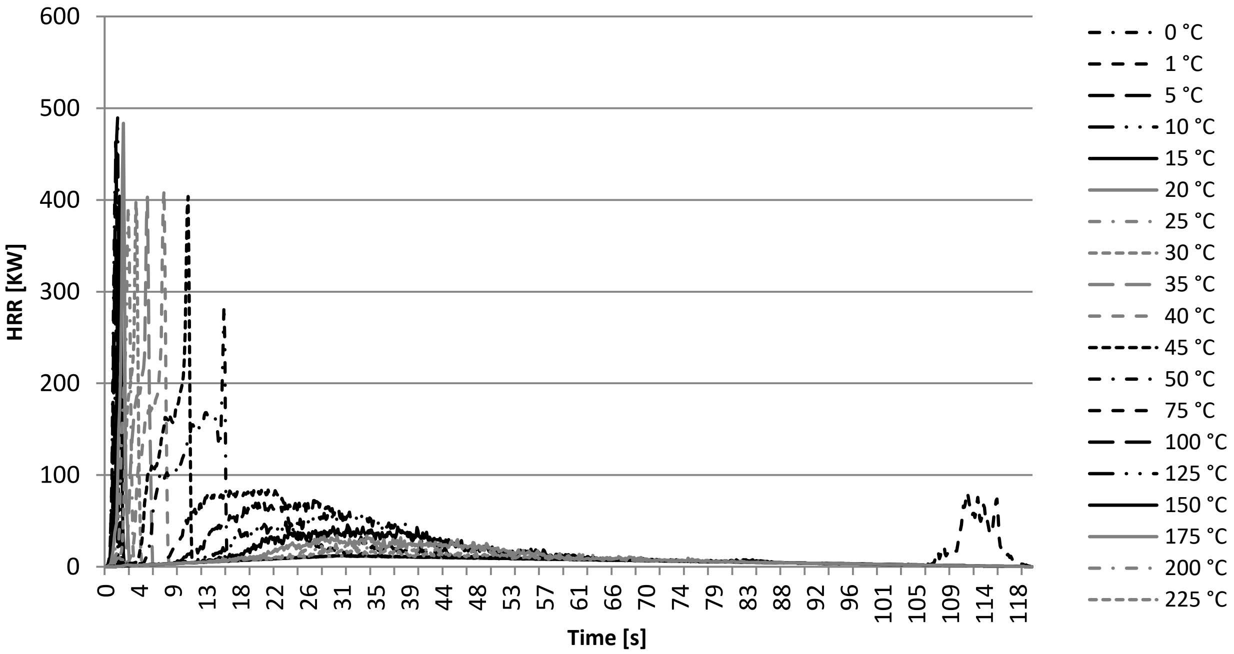



Figure 77 – Influence of Reference Temperature parameter in FDS Simulations

A heat rate of 0 leads to a HRR curve conforming to the HRR curve set by the FDS ramp-up function. The higher the heat rate is set the higher is the HRR peak as well and the sooner the burning period starts as shown in Figure 78. Towards the end of the burning period all HRR curves converge to almost similar values.

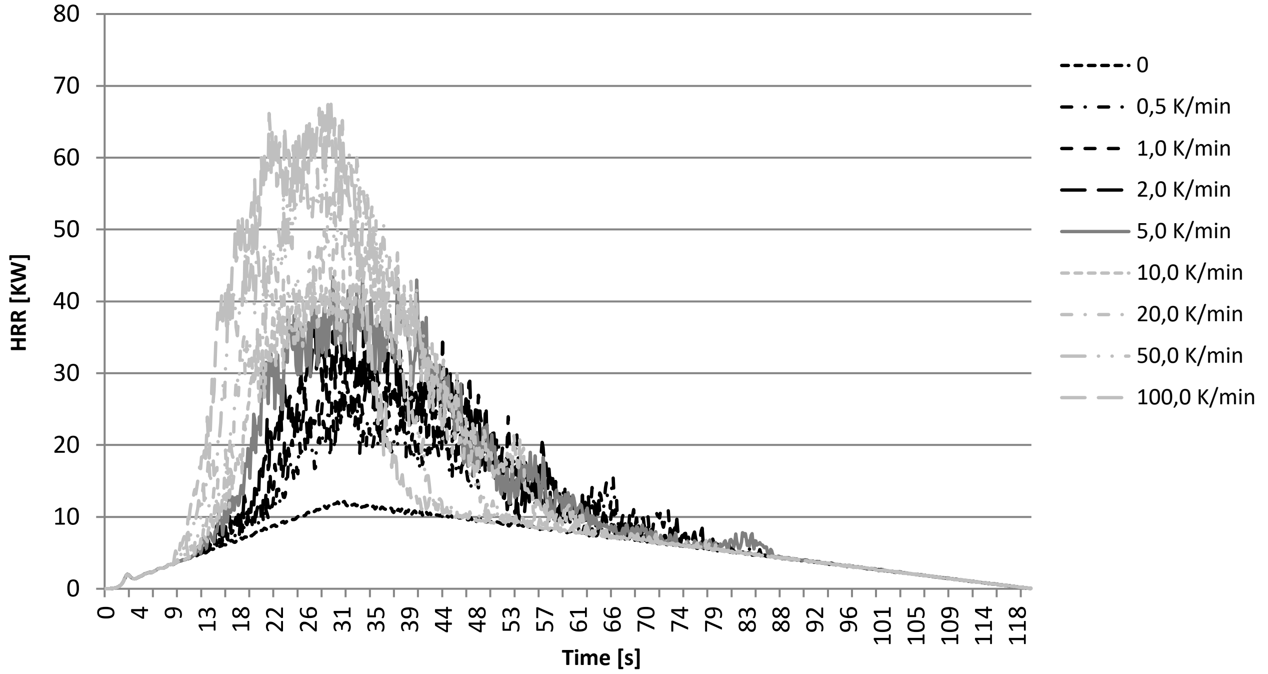



Figure 78 – Influence of Heat Rate Parameter in FDS Simulations

The pyrolysis range does not affect the burning behaviour that much as shown in Figure 79. Thus, it can be used for the final adjusting of the HRR peak.

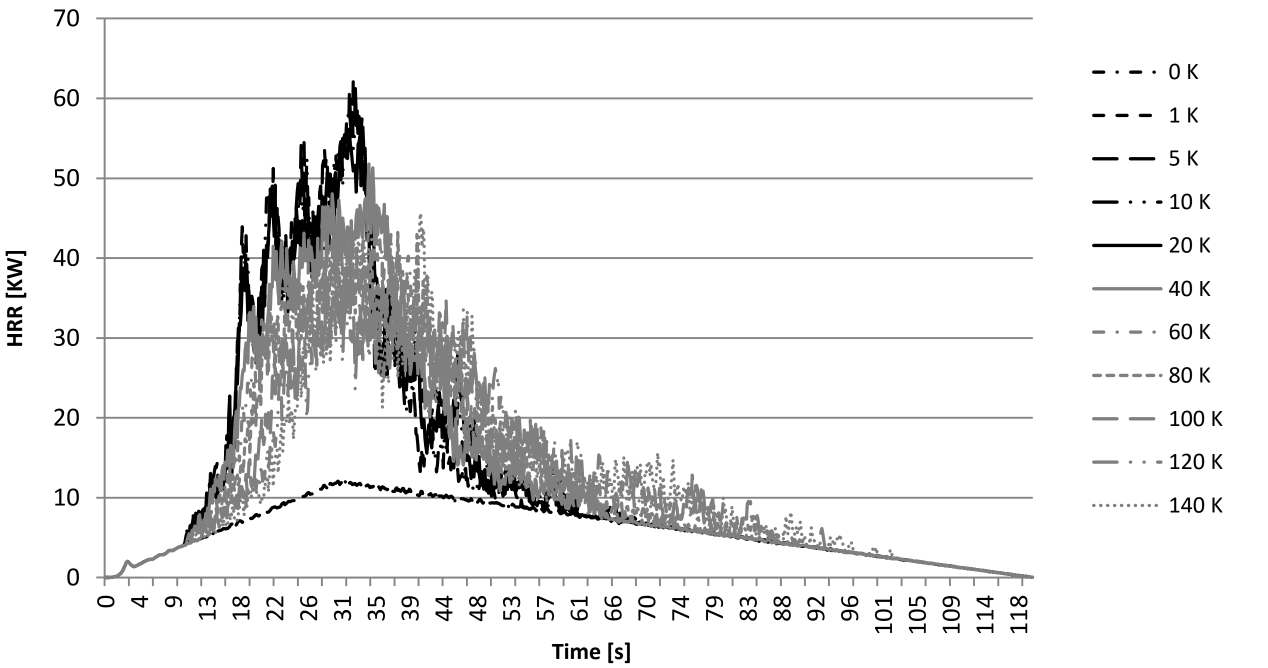



Figure 79 – Influence of Pyrolysis Range Parameter in FDS Simulations

Due to the fact that the mass fraction exponent defines the percentage portion which cannot exceed 100 %, the mass fraction exponent of FDS will deliver reasonable values between 0 and 1 only. The higher the mass fraction exponent is set the steeper is the HRR gradient emerging after ignition as shown in Figure 80.

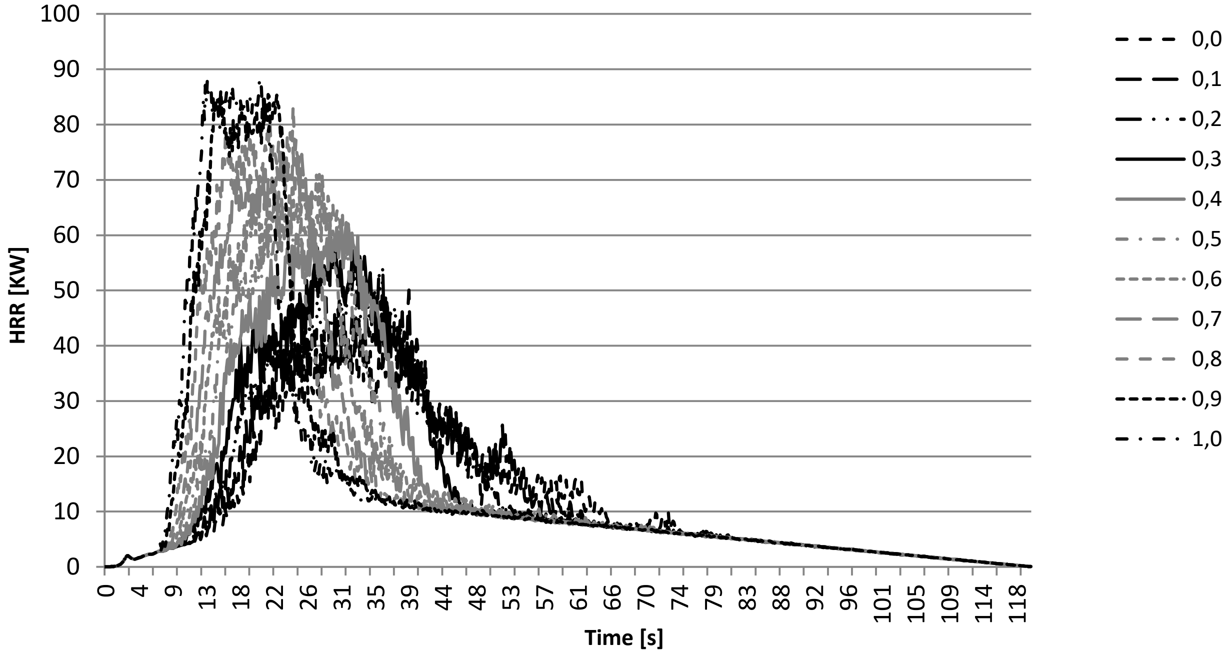



Figure 80 – Influence of Mass Fraction Exponent Parameter in FDS Simulations

Heat of reaction (exothermic) delivers reasonable values beginning from 1000 kJ/kg since values below are nearby the FDS ramp-up function or fluctuate chaotically as shown in Figure 81. Values above 1000 kJ/kg do not affect the burning behaviour that much since they lead to nearly similar results as shown in Figure 81.

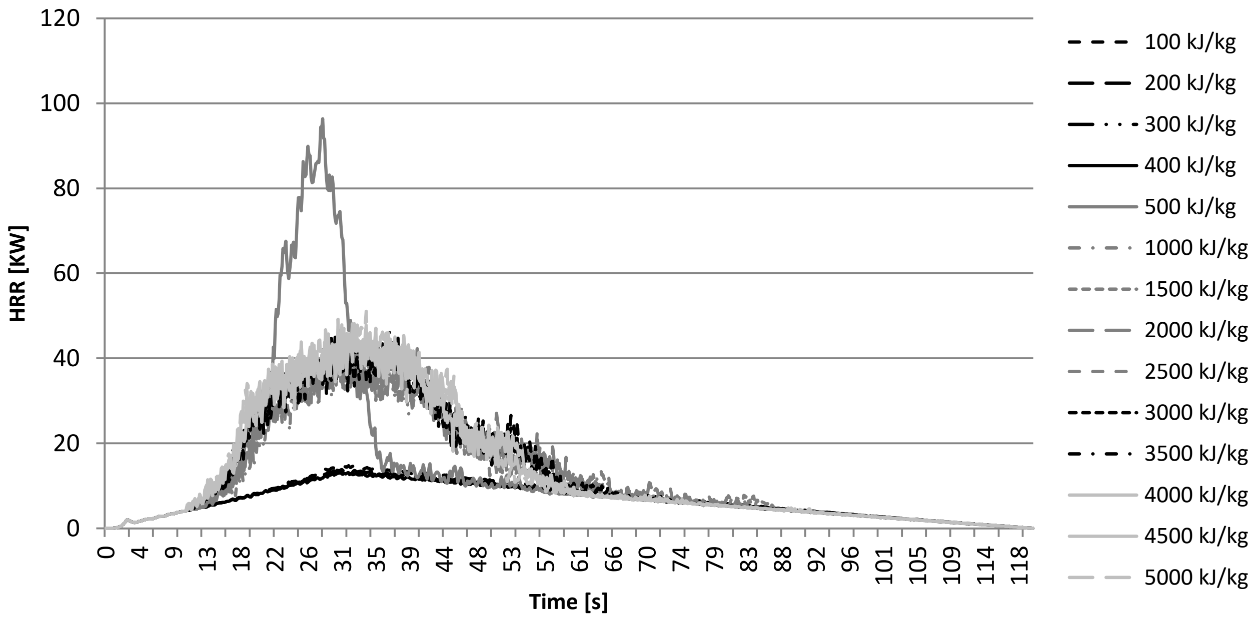



Figure 81 – Influence of Heat of Reaction Parameter in FDS Simulations

Applying these findings have led to the design of a new FDS material which is called 'PU Foam Seat' in the dissertation at hand. In Table 30 the FDS material parameter of 'PU Foam Seat' and its origin 'PU Foam Basic' are summarised for comparison.

Table 30 – FDS Material Data of PU Foams applied

| FDS Material Data of PU Foams applied | | |
|---|---|---|
| **Parameter** | **PU Foam Basic** | **PU Foam Seat** |
| Density [kg/m³] | 64.00 | 40.00 |
| Specific Heat [W/mK] | 1.00 | 1.00 |
| Conductivity [W/mK] | 0.05 | 0.05 |
| Emissivity [1] | 0.90 | 0.90 |
| Absorption Coefficient [1/m] | 50.00 | 50.00 |
| Heat of Combustion [MJ/kg] | 25.00 | 30.00 |
| Reference Temperature [°C] | 350.00 | 200.00 |
| Heating Rate [K/min] | 5.00 | 5.00 |
| Pyrolysis Range [°C] | 80.00 | 100.00 |
| Mass Fraction Exponent [1] | 1.00 | 1.00 |
| Heat of Reaction [kJ/kg] | 1500.00 | 250.00 |
| Fuels Vapour Yield [1] | 1.00 | 0.12 |
| Water Vapour Yield [1] | 0.00 | 0.10 |
| Residue Yield [1] | 0.00 | 0.00 |

#### 4.1.3.2 Interior Plastics

Interior parts of road vehicles are predominantly made of plastic materials based on polyurethane, acrylonitrile butadiene styrene, polyvinyl chloride, polyamide and polyester as summarised in Table 3. It must be noticed that these materials are always a mixture of different ingredients. When parts containing polyurethane or acrylonitrile butadiene styrene are meant, the predominant ingredient is only focused at, which leads also to a simplification for the FDS bus models.

Since it is extremely extensive to calibrate material data, it was tried to minimise the amount of different material types for simulations. First PUR was modelled as presented in Chapter 4.1.3.1. In next step it was tried to adjust the FDS material parameters of ABS for simulations. Because the material parameters of 'PU Foam Seat' applied on all bus interior materials implemented have already delivered convincing fire simulation results, further efforts for adjusting ABS material parameters were skipped and a general plastic interior material for plastic components excepting seats was established based on 'PU Foam Seat'. In contrast to the basic material 'PU Foam Seat', it is called 'Interior material' in the dissertation at hand and the density was changed to 80 kg/m³.

## 4.2 Numerical Simulations

In this chapter the material data examined, the fire scenarios modelled and the bus models established are combined for simulating complete bus fire scenarios. Prior, the material data obtained for FDS applications were used to simulate fire scenarios of areas in a bus which are typically causes of fires. Following this, the typical causes of bus fires simulated were implemented into the bus models presented in Chapter 4.1.2.

In FDS there are principally two ways of creating a fire. On the one hand the heat release rate per unit area (HRRPUA) of a fire can be predefined. On the other hand also the heat of vaporization and the heat of combustion can be defined for a material getting burn. Using the latter method is more problematically concerning adjusting the burning rate which depends on the radiation feedback from the combustion in the gas phase to the surface and in addition depends on the heat transfer in the combusted material [compare with 64]. Therefore the first method of applying a prescribed heat release progress was used in all simulations run.

CFD calculation of smoke and fire spread are inherently sensitive to numerical characteristics and to physical parameters as well. The most important numerical parameter is the size of the cell grid which is the smallest single volume where the solution to the problem is calculated. In order to obtain a proper numerical solution the size of the cell grid must not be too large. This means that in a large cell grid the total number of cell grids decreases and therefore the computation time also decreases. However, too rough grids mean that the numerical solution becomes a poor approximation of the analytical solution. It is also possible that the computations do not converge to a solution, meaning that no result is obtained. Since a parameter study concerning an optimum cell grid was already performed in a student research project executed at BAM [67], the width of cubical cells gained was overtaken in the simulations of the dissertation at hand.

### 4.2.1 Ignition Scenarios

Before simulating complete bus fires, different ignition scenarios focusing at areas being typically causes of bus fires were numerically investigated.

#### 4.2.1.1 Passenger Seat

Passenger seats are obviously parts in a bus getting attacked by arson. Often lighters or crumpled newspaper ignited are used for these arson attacks. Therefore a passenger seat getting affected by arson was chosen to be ignition scenario. In particular a paper pillow conforming to DIN 5510 igniting is applied as source of fire and has been already investigated in Chapter 4.1.3.2.

#### 4.2.1.2 Lavatory

Beside passenger seats the lavatory is also typically targeted when getting attacked by arson and is at least a hidden area where sometimes passengers smoke furtively a cigarette. Especially the Hanover bus fire demonstrated that the lavatory interior itself can be the area where the initial fire development occurs [62]. Thus, the fire scenario of a lavatory getting ignited was investigated further as well.

In the simplified bus model from a student research project executed at BAM [67] the ignition of the lavatory was implemented by applying the HRRPUA feature set to 700 kW/m² at the lavatory floor which can be indicated by the red surface on lavatory floor visible in Figure 82 on the left. The fire spread from the lavatory interior into the bus interior is realized by implementing the FDS object removal feature applied on the lavatory door. By removing the lavatory door the hidden developed fire raises to an enormous flash fire as shown in Figure 82 on the right since hot incompletely combusted smoke gases, which have been generated within the lavatory enclosure due to reduced oxygen supply, are immediately mixing with fresh air from the passenger cabin and the smoke gas temperature is hot enough for igniting the mixture as well.

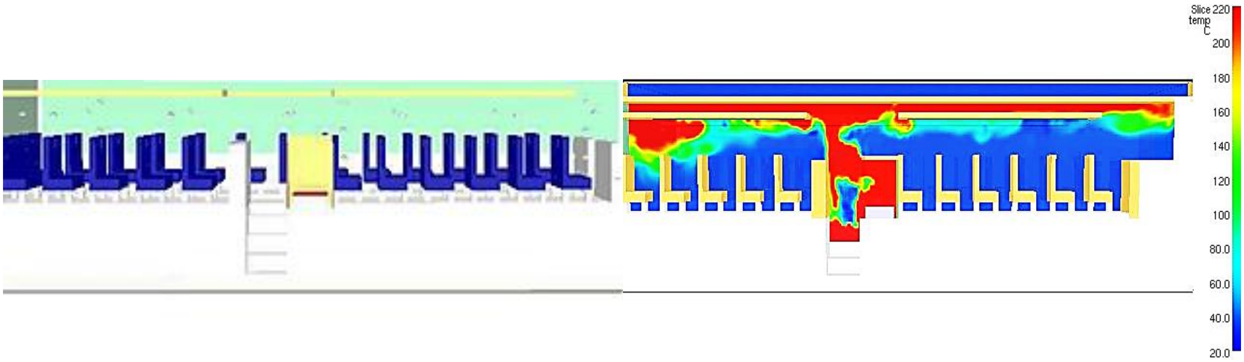


Figure 82 – Lavatory Getting Ignited in Initial Bus Fire Model [67]

Since the official survey report of the 2008 Hanover bus fire [70] was available and stated that a break in a cable located in a cable duct adjacent to the lavatory was established to be the initial fire source, this ignition scenario was implemented in the fire simulation of the diploma thesis executed at BAM [69]. The ignition source is highlighted by the red surface shown in Figure 83 on the left. In this scenario the fire spread from the lavatory interior into the passenger compartment was also realised by implementing the FDS object removal feature applied for the lavatory door. The flash fire occurring is shown in Figure 83 on the right and is very similar to the one seen in the initial bus fire model.

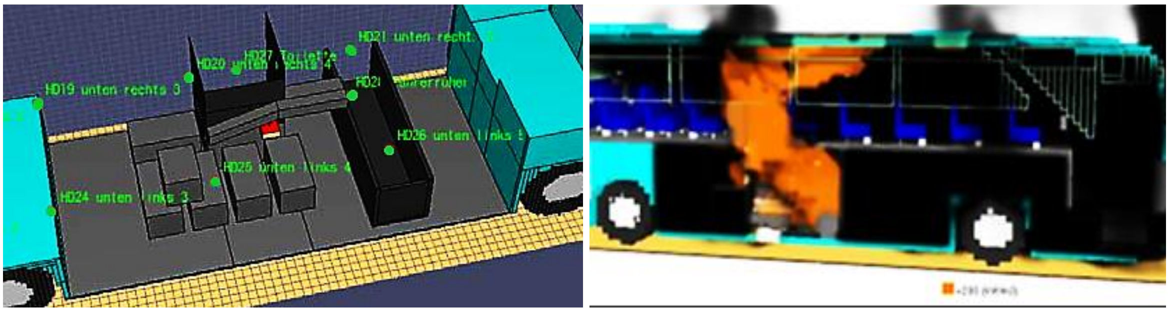


Figure 83 – Lavatory Getting Ignited in Hanover Bus Fire Model [69]

Due to the implementation of ventilation in bus fire simulations as shown in Chapter 4.1.2.3, the ventilation aspect was also investigated in the lavatory interior available in the bus model of a 2012 coach. Especially when the lavatory is involved being cause of fire as occurred in the Hanover bus fire [70], the ventilation can have a major impact of the following fire development there. In the simulation scenario with the ventilated lavatory the initial fire development of the Hanover bus fire was tried to reconstruct in more detailed.

Since the fresh air supply fan implemented in lavatories is used fairly seldom, this function was skipped in this lavatory model simulated. Nevertheless, when the bus is operating the air streams through the bus lavatory. In detail fresh air comes from louvers towards the luggage compartment and finally leaves the lavatory interior through the fresh air supply fan towards the street as shown in Figure 89 on the left. The reason for this air stream is the ventilation system typically in a bus operating which generates an overpressure in the luggage compartment as described in Chapter 4.1.2.3.

Immediately when the lavatory door was getting opened, the air flow going outwards to the street reverses and goes into the passenger cabin. This effect can be seen in Figure 84 which is comparing the air streaming in the lavatory while its door is closed on the left against the door is opened a second later on the right. In this very moment fresh air from outside gets rapidly sucked in from outside since the hot air from lavatory spreads into the passenger compartment. In addition the flash fire occurring in the passenger compartment is fuelled by mixing process of incomplete combustion gases with the fresh air of the passenger cabin. This generates a local vacuum in the bottom area of the lavatory interior which sucks in even more fresh air from outside visible by the red coloured air jet in Figure 84 on the right.

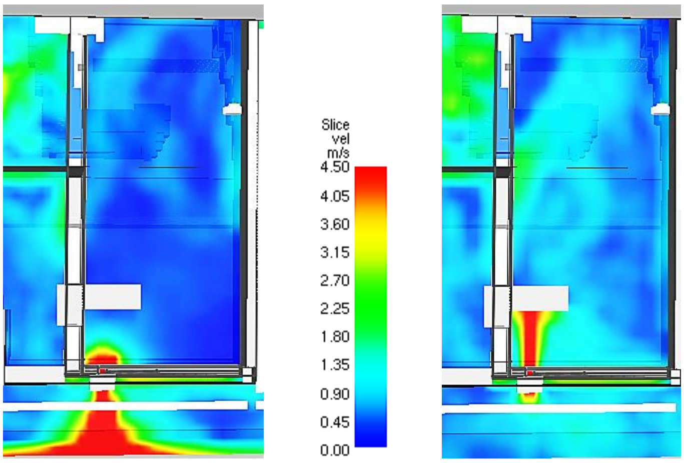
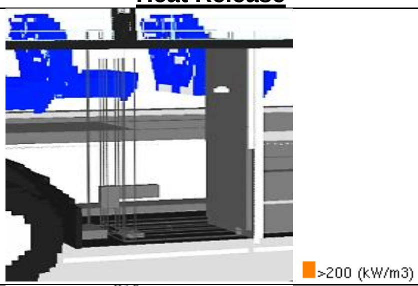
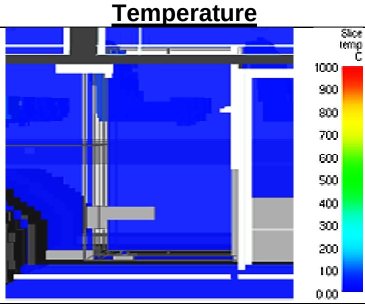
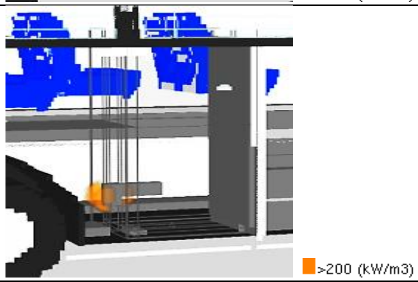
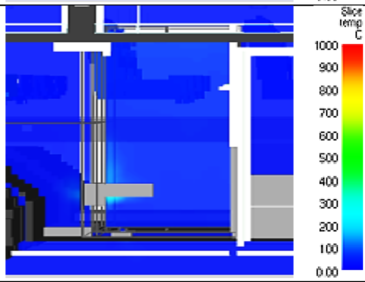
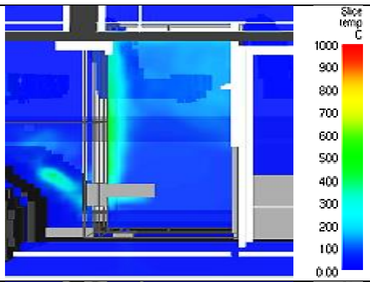


Figure 84 – Airstream in Lavatory Interior of an Operating Bus

The ignition itself is implemented by a small plastic part mounted outside and getting ignited by a predefined HRRPUA of 500 kW/m² below as shown in Table 31. In addition a louver above enables the entrance of fire into the lavatory interior. In difference to the lavatory ignition applied in the initial bus model and the Hanover bus fire Model, in which the lavatory respectively the cable duct was directly inflamed, the lower edge of the cable duct gets flamed only. The picture series summarised and commented in Table 31 are explaining the ignition and the following fire propagation in the lavatory ventilated stepwise. For showing this more clearly the lavatory is figured transparent and is indicated by grey outlines only.

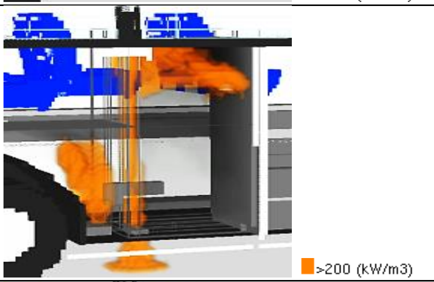
Table 31 – Ignition of Ventilated Lavatory

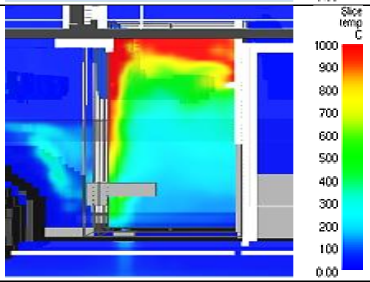
| **Ignition of the Ventilated Lavatory** | | |
|---|---|---|
| **Heat Release** | **Temperature** | **Description** |
|   |   | 00:00<br>Before ignition |
|   |   | 00:01<br>Cable duct ignited |




00:10

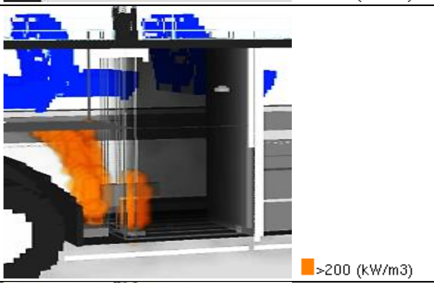
Lavatory interior entered by fire

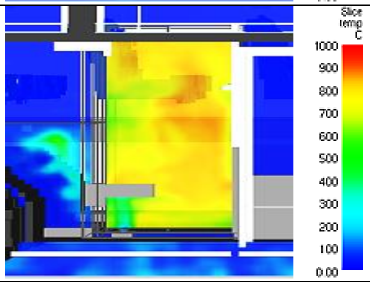





00:22

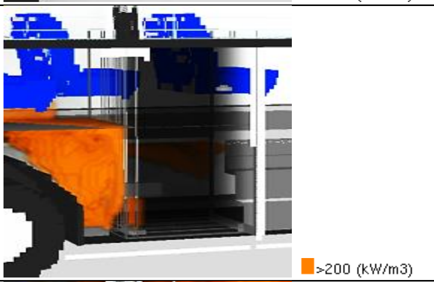
Flash-over phase of compartment fire in lavatory interior

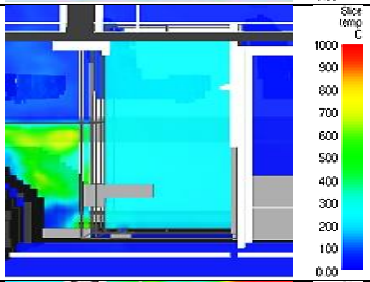





00:30

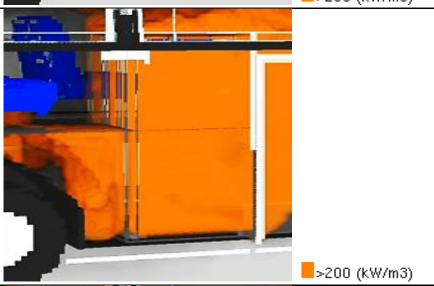
Oxygen content in lavatory decreasing

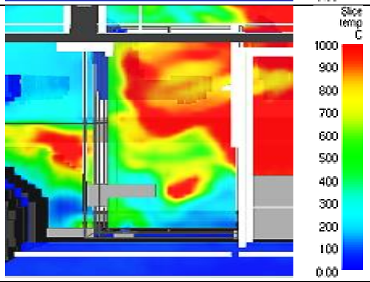





00:59

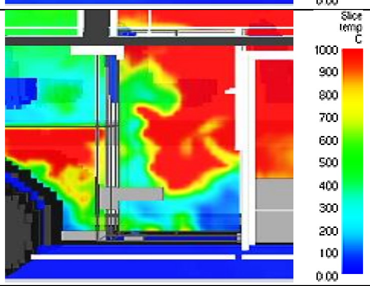
Lavatory before door is getting opened






01:00

Lavatory door got opened




01:05

5 s elapsed after lavatory door opening

#### 4.2.1.3 Engine Compartment

While SP was developing the test rig for assessing fire suppression systems in engine compartments of SP-Method 4912 [60], numerical CFD simulations were additionally run for supporting the development at this stage. First step was to model the complete test rig in FDS including all components. Figure 85 shows the original test rig used in the fire lab on the left and its CAD model applied for further simulative investigations on the right. The test rig represents a typical bus engine compartment and was condensed to its main influencing parts concerning fire development and suppression only.

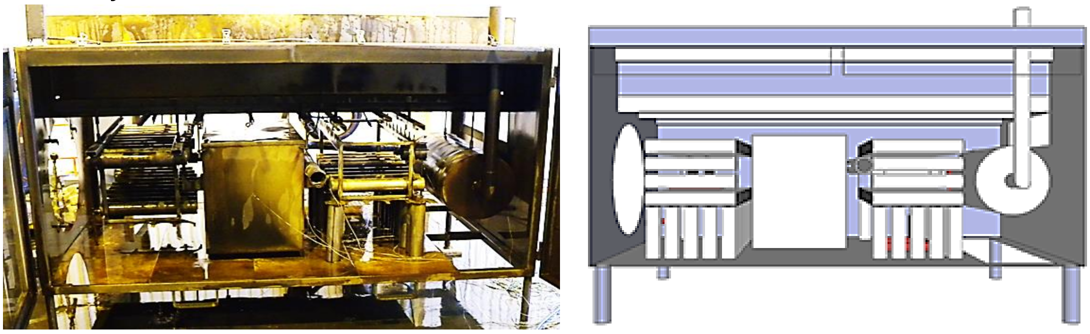


Figure 85 – Original and CAD Model of Engine Compartment Test Rig acc. SP-Method 4912

The FDS model was derived from the CAD model and rendered to a 2 cm cubical cell grid. In total the model consists of 558,000 cells. Firstly the air flow generated by the cooling fan was investigated further. The fan is externally positioned at the left circular opening and produces laminar incoming air flow with a velocity of 25 m/s as measured in the original test rig.

From simulation results shown in Figure 86 on the left it can be gathered that the simulated engine compartment consists of two different ventilation areas. Both the left section up to the engine block and the area a bit beneath the ceiling are ventilated well. In contrast to this the right section from the engine block up to and around components installed is ventilated less. Thus, both fire source areas located to the left and the right of the engine block are subjected to different ventilation conditions during the test procedure. In addition to this, the strong air flow beneath the ceiling produces very demanding conditions in the area where the nozzles are installed.

Figure 86 on the right illustrates the same test rig supplemented with an additional metal plate placed 8 cm behind the inflow air opening. This metal plate leads to a reduced airflow in the entire engine compartment space except the area directly adjacent to the metal plate. On the other hand the engine compartment can be also divided into a moderate ventilated and another almost unventilated section around the obstacles to the left and right of the engine block. Further investigations were performed without the metal plate implemented additionally since the ventilation conditions with it would not truly reflect the conditions in real bus engine compartments.

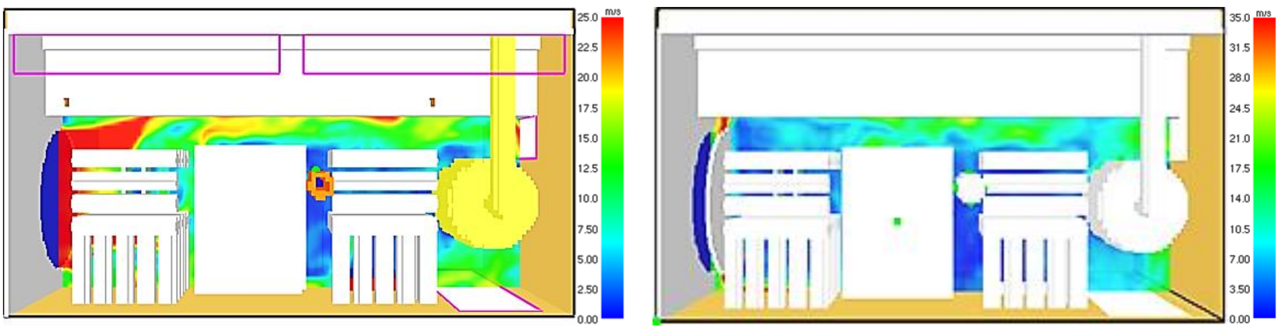



Figure 86 – Different Modes of Engine Compartment Test Rig simulated with FDS

In next step a diesel spray fire simulating a fuel pipe leaking was implemented in the test rig. Figure 87 shows the pre-burning in a fire test and simulated. Pre-burning is needed to heat up the test rig to real condition before fire suppression will be activated. In the numerical simulation this fire scenario was achieved by the diesel fuel spray feature available in FDS. For igniting the diesel spray a predefined HRRPUA on a small obstruction below the spray device was implemented.

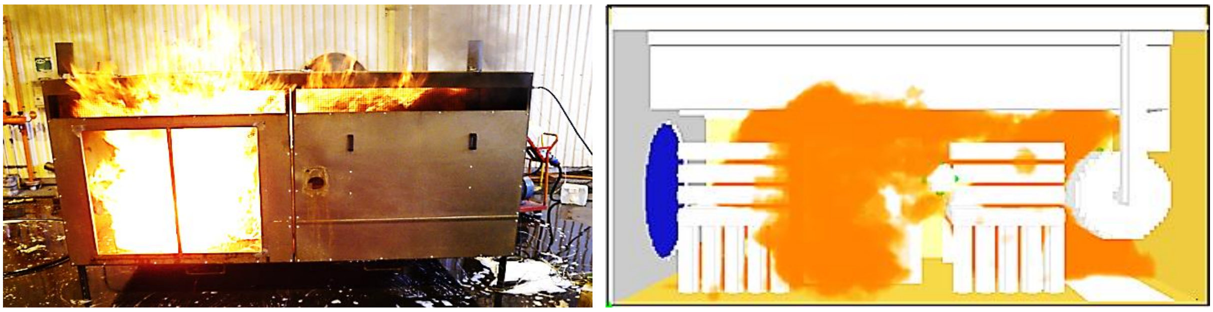


Figure 87 – Preheating the Engine Compartment Test Rig by Flaming

Another preheating approach successfully investigated in the test lab was to warm up single components by external heaters which were then removed from test rig immediately prior to activating the fire suppression. Simulating this was achieved by pre-defining surface temperatures at start of simulation. Temperatures measured in reference buses and applied in simulations are listed in Table 32.

Table 32 – Surface Temperatures Predefined for Simulating Preheating

| **Surface Temperatures of Engine Compartment Parts** | |
|---|---|
| **Part** | **Surface Temperature** |
| Engine Block | 90 °C |
| Exhaust pipe | 350 °C |
| Manifold | 550 °C |
| Muffler | 350 °C |

In Figure 88 the preheating scenario is shown by two different temperature view modes available in FDS at 5 min elapsed. In particular the surface temperatures were predefined and the diesel spray fire was running. The deep blue surfaces of obstacles and the enclosure visible in Figure 88 on the left indicate that such parts could only slightly warm up by the diesel spray fire. Contrary to this the air temperatures shown in Figure 88 displays high temperatures in the same area. This proves that the preheating by inflaming does not work well in FDS. However, these results states that this engine compartment test rig features two different sections of air temperatures. The colder section is located left of the engine block reaching not more than 500 °C even while being close to flames. On the other side of the engine block the air temperatures reached almost 1000 °C.

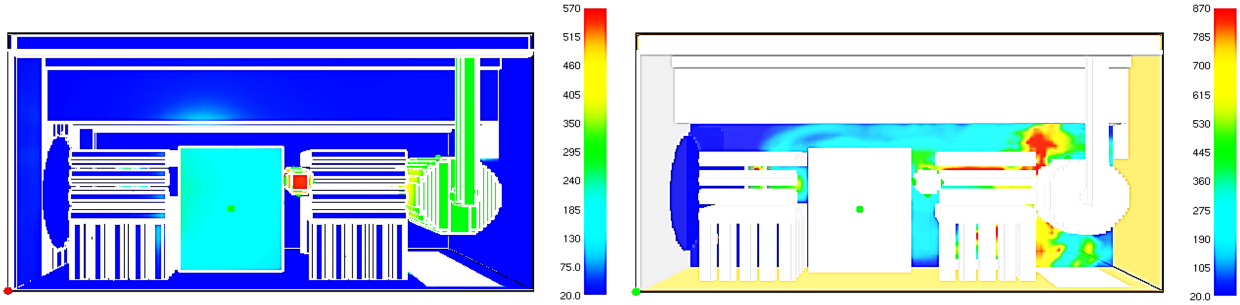



Figure 88 – Preheating the Engine Compartment Test Rig by Flaming

In the FDS model of the engine compartment test rig also three different cooling approaches were investigated. In detail the FDS sprinkler function with and without cooling air as well as cooling air only were simulated as shown in Figure 89. The sprinkler function emits water droplets with a temperature of 20°C for reducing heat energy in fires. In contact with a solid the droplets cool the surfaces they collided with as visible on the left enclosure part and at the engine block in the middle column of Figure 89. However, flames, smoke and surrounding air heated up will not be cooled. Thus, the cooling effect of a fire suppression process cannot be simulated realistically with FDS. Main reason for this is that the cooling by water droplets is not implemented in FDS.

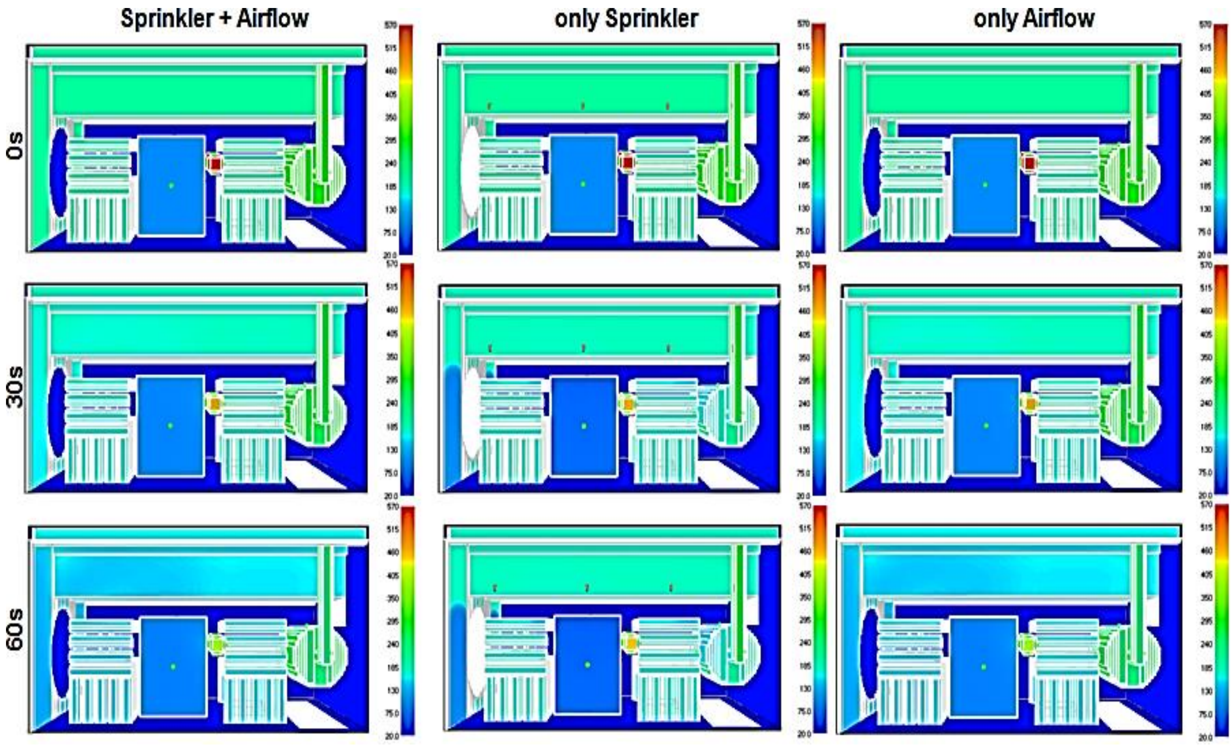



Figure 89 – Cooling the Engine Compartment Test Rig by different Approaches

### 4.2.2 Bus Fires Scenarios

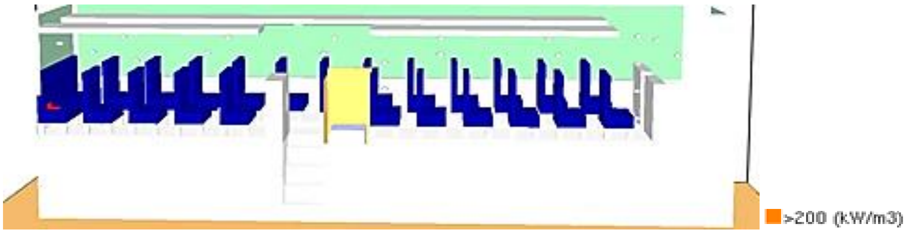
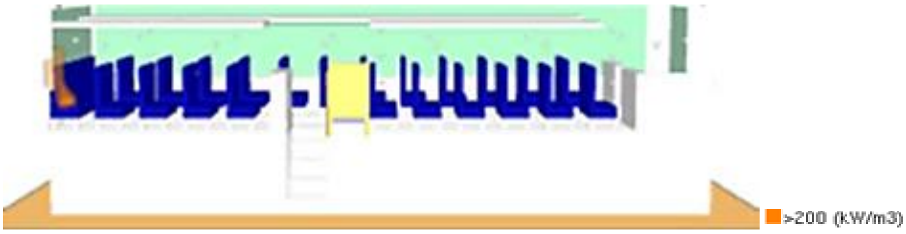
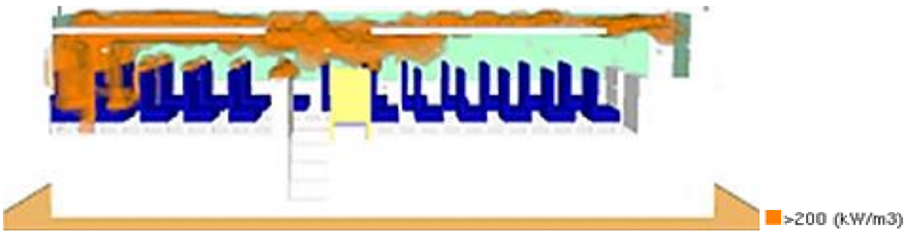
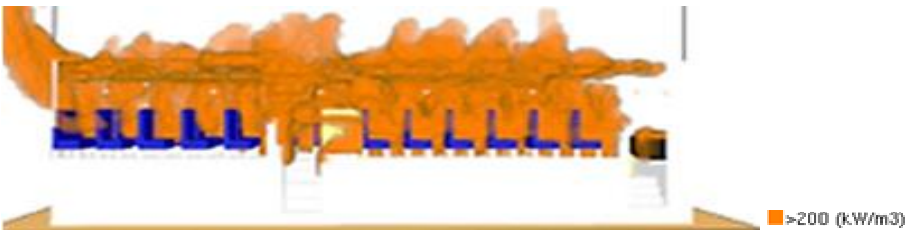
In the dissertation at hand three different fire scenarios were examined. In scenario 1 a passenger seat is getting ignited for simulating an arson attack on a passenger seat. Scenario 2 simulates the severe 2008 Hanover bus fire which commenced with a fire in the lavatory. Finally an engine compartment is getting ignited in scenario 3 simulating the most common fire source in buses.

#### 4.2.2.1 Arson Attack on a Passenger Seat

Before simulating the Hanover bus fire which reconstructs the fire development in the severe bus fire occurred in 2008 near Hanover, an arson attack on a passenger seat was examined first. Compared to the other fire scenarios following the implementation of this scenario in the bus models is generally less complex. However, passenger seats are typical targets of arson attacks and therefore this scenario was investigated further.

In the initial bus model the fire source is applied by the Heat Release Rate Per Unit Area (HRRPUA) of 500 kW/m² on a 0.2 m² surface area located on a passenger seat base in the last seat row. For explaining the ignition and the following fire propagation in the bus stepwise, the sequence of fire development is summarised and commented in Table 33.

Table 33 – Arson Attack on Passenger Seat in Initial Bus Model

| Arson Attack on a Passenger Seat in the Initial Bus Model | |
|---|---|
|   | 00:00<br><br>Before ignition |
|   | 00:10<br><br>Ignition completed |
|   | 01:00<br><br>Seat completely burning and ceiling filled with smoke |
|   | 02:00<br><br>Next seat row ignited and flash-over started |
|   | 3:30<br><br>Passenger compartment completely burning |

From this simulation it can be gathered that the fire source based on an arson attack can be principally used as ignition source for bus fire simulations. In fact the simulation results illustrate that the burning rate of passenger seats itself is not the main hazard in this fire scenario but releasing combustible fire gases spreading along the ceiling and causing flash-over instead.

To evaluate the initial bus fire model the simulation results were compared to several photos and videos of real bus fires as shown in Figure 90. This proves that FDS can simulate the fully developed fire phase of a bus fires.

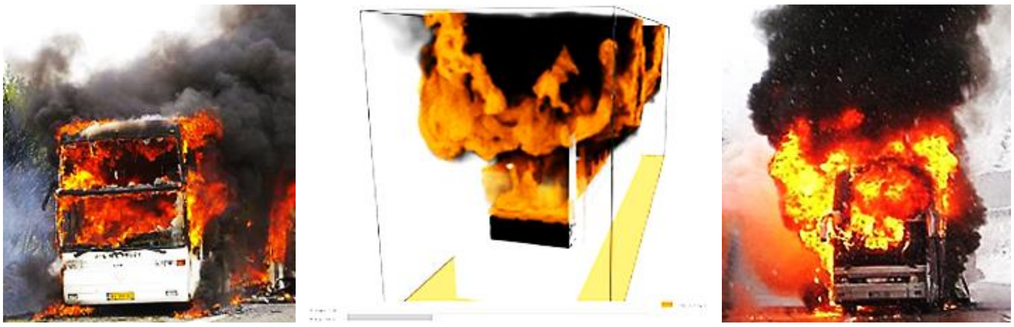
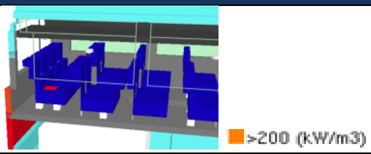
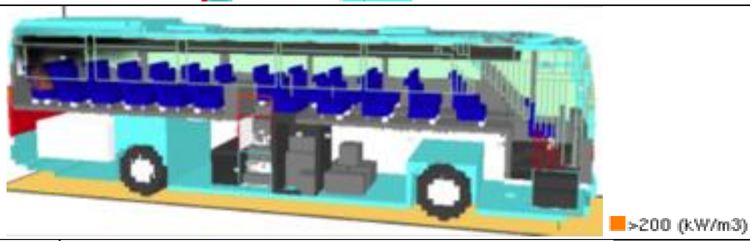
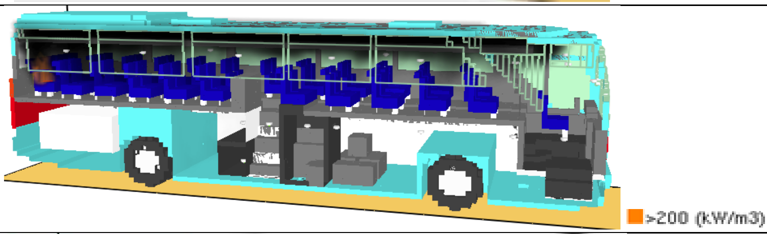
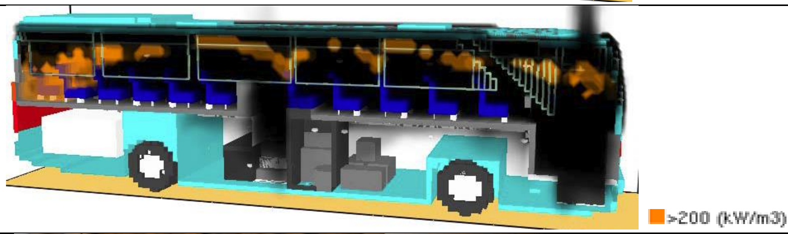
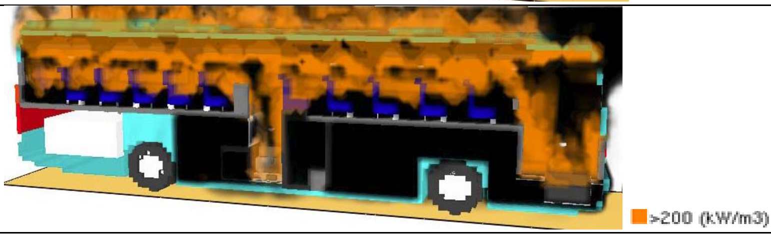


Figure 90 – Evaluation of Results Simulated with Initial Bus Model [67]

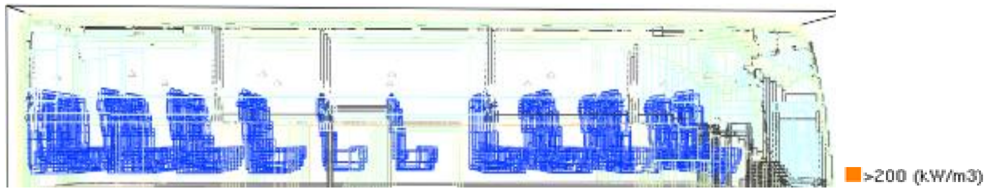
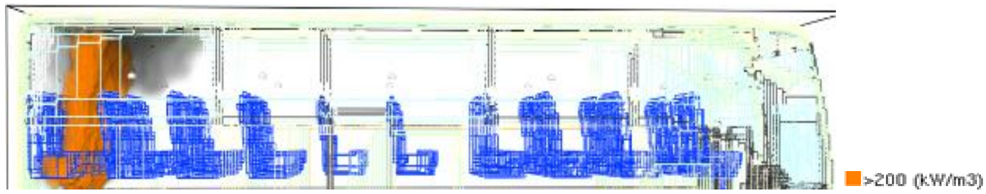
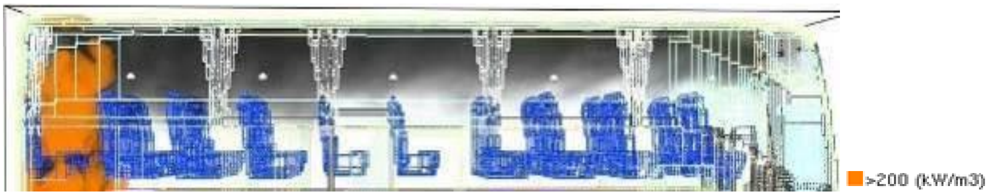
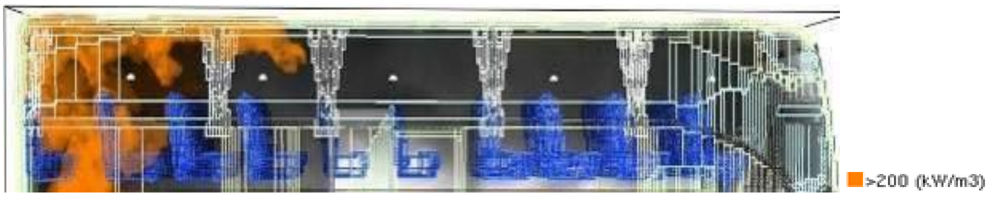
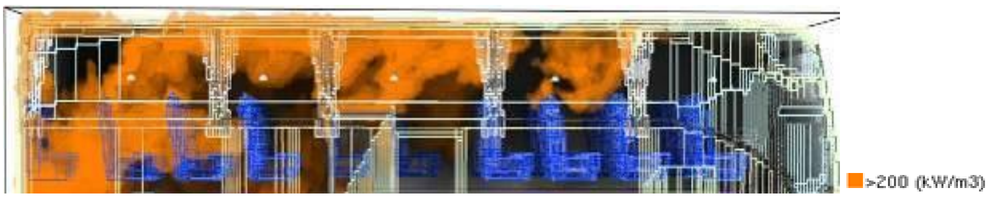
The same fire scenario was simulated in the Hanover bus fire model as well. In contrast to the initial bus model it features another distribution of passenger seats. The fire source was transferred from the initial bus model and was located at the nearly the same location in the Hannover bus model. For explaining the ignition and the following fire propagation in the bus stepwise, the sequence of fire development is summarised and commented in Table 34.

Table 34 – Arson Attack on Passenger Seat in Hanover Bus Fire Model

| Arson Attack on a Passenger Seat in the Hanover Bus Fire Model | |
|---|---|
|   | 00:00<br><br>Before ignition |
|   | 00:10<br><br>Ignition completed |
|   | 01:00<br><br>Seat completely burning and ceiling filled with smoke |
|   | 02:00<br><br>Next seat row ignited and flash-over started |
|   | 3:30<br><br>Passenger compartment completely burning |

The same fire scenario was simulated in the bus model of a 2012 coach as well. In contrast to the simulations run with this fire scenario before, ventilation is implemented as described in Chapter 4.1.2.3 and the ramp-up function simulating the paper cushion ignition was applied as described in Chapter 4.2.1.1. Also the seat distribution differs compared to other bus models. For explaining the ignition and the following fire propagation in the bus stepwise, the sequence of fire development is summarised and commented in Table 35.

Table 35 – Arson Attack on Passenger Seat in Bus Model of a 2012 Coach

| Arson Attack on a Passenger Seat in the Bus Model of a 2012 Coach | |
|---|---|
|  | 00:00<br><br>Before ignition |
|  | 00:10<br><br>Ignition completed |
|  | 01:00<br><br>Seat completely burning and ceiling filled with smoke |
|  | 02:00<br><br>Next seat row ignited and flash-over started |
|  | 02:30<br><br>Fire reached the lavatory |
|  | 3:30<br><br>Passenger compartment completely burning |

The fire development simulated based on the fire scenario of an arson attack on a passenger seat is very similar across all bus models, although in contrast to the other bus models the ventilation system was activated and a lower heat release rate for ignition was applied in the bus model of a

2012 coach. Furthermore, the comments for the fire propagation steps and their point in time are identic to the one noted in the initial bus model and in the Hannover bus fire model. However, an additional step for 2.5 min elapsed was included for the bus model of 2012 coach since the fire propagation did not only take place along the ceiling but also from seat to seat quickly. This happened since the ventilation system was activated. Finally this proves that the ventilation system implemented has also a significant influence on the fire development in this scenario.

#### 4.2.2.2 Hanover Bus Fire

The simulation of the Hanover bus fire reconstructs the severe 2008 bus fire shown in Figure 91 in which the fire commenced at the lavatory and in which later a flash fire overcame the complete passenger compartment while driving. In the dissertation at hand this scenario was predominantly used to establish the bus fire models.

Figure 91 – Bus Fire in November 2008 near Hanover

Reports from fire brigades were not available for obtaining more detailed information about the fire source. Thus, issues and details needed to be adopted from witness statements of the news first as done for the initial bus model from a student research project executed at BAM [67]. Surviving witnesses reported that for the source of ignition the lavatory needs to be assumed from which a flash fire rapidly extended along the whole passenger compartment when a passenger opened the lavatory door. Thus, in the initial bus model the fire source was included into the lavatory on the floor by adopting a predefined HRRPUA. In addition doors getting opened and windows getting destroyed were implemented based on the FDS object removal features and were triggered at a specified point in time. In particular the lavatory door will be automatically removed at 60 s simulation time elapsed. This time span includes the ignition and the initial fire development in the lavatory interior. The smoke accumulation and the heat releasing in the lavatory interior at 59 s elapsed is shown in Figure 92 on the left. When removing the lavatory door the hot incomplete combustion gases of the lavatory interior are immediately spreading out and mixing with air from the passenger cabin. This promptly entails a flash over through the complete passenger cabin as shown in Figure 92 on the right which displays the fire spread at 1 s elapsed after removing the lavatory door.

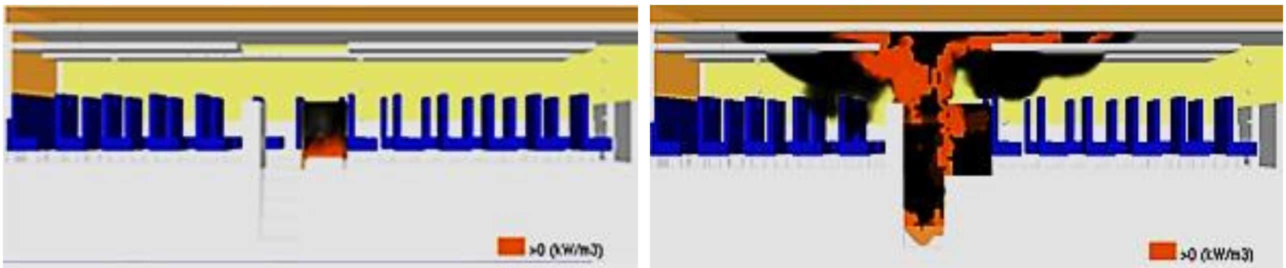



Figure 92 – Scenario of Hanover Bus Fire Source in Initial Bus Fire Model

Later, when the official survey report [70] was available, several details of this bus fire scenario were modified for the dissertation at hand such as assuming the driver needed 15 s to stop the bus. Thus, the outer doors of the Initial Bus Model will be opened when 75 s simulation time elapsed. The implementation of outer doors getting opened is based on the object removing feature as applied for the lavatory door.

For simulating the ignition a 0.01 m² surface area providing a HRRPUA of 500 kW/m² [69] was implemented beneath the cable. Figure 93 shows the location of the ignition source implemented in the Hanover Bus Fire Model.

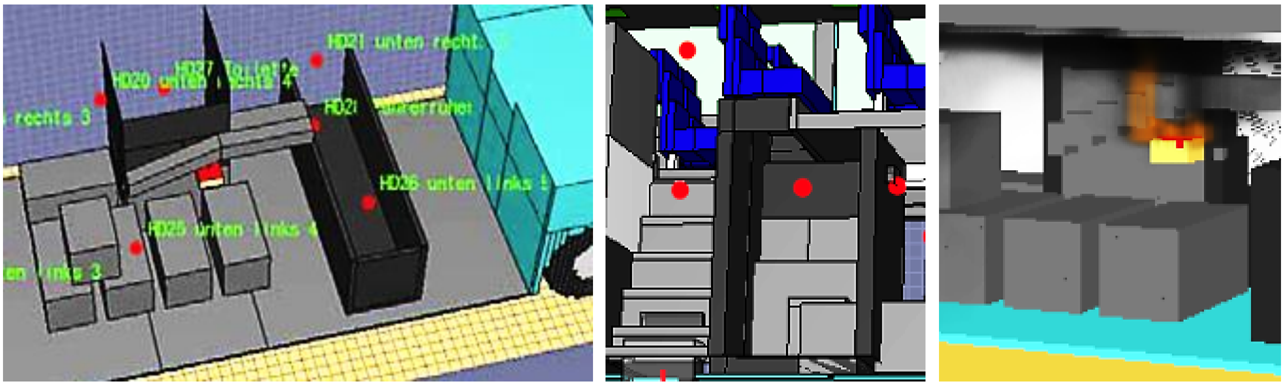


Figure 93 – Scenario of Hanover Bus Fire in the Hanover Bus Model [69]

Due to the fact that the ventilation system has a strong influence on the fire behaviour in a bus the ventilation feature developed in the bus model of a 2012 coach as shown in Chapter 4.1.2.3 was adopted. In doing so, the overpressure in the passenger cabin caused by inflowing air blocks the smoke spread coming from the luggage compartment. This effect shown in Figure 94 on the left reflects the description available in the official survey report [70] which was also pre-simulated in Chapter 4.1.2.3. Figure 94 shows also the hidden fire propagation along the luggage compartment and reflect a witness statement from survey report saying that smoke came out of the driving bus while being unnoticed by the driver and passengers. The initial flash fire entering the passenger cabin when the lavatory door was opened is shown in Figure 94 on the right.

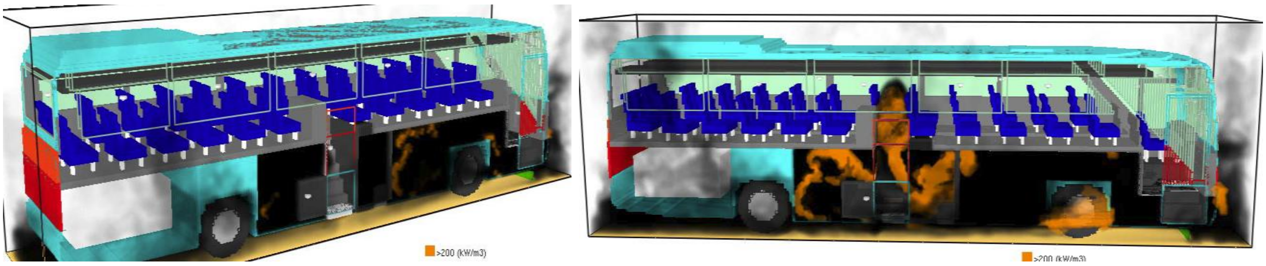
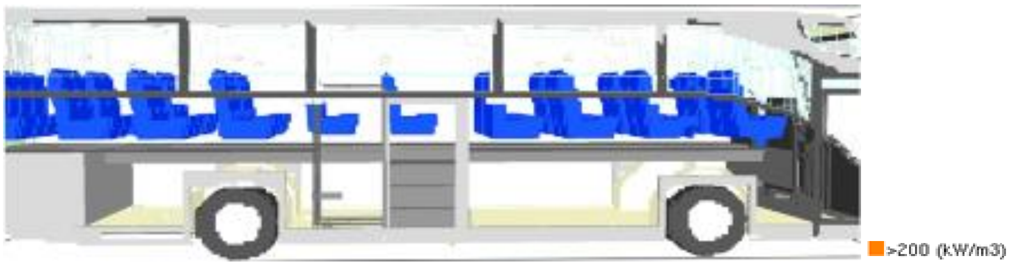
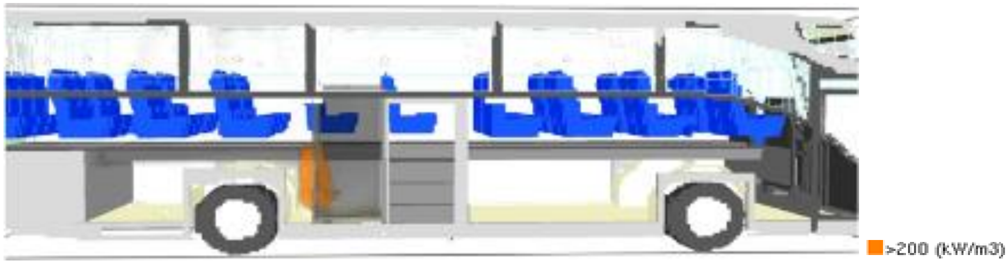
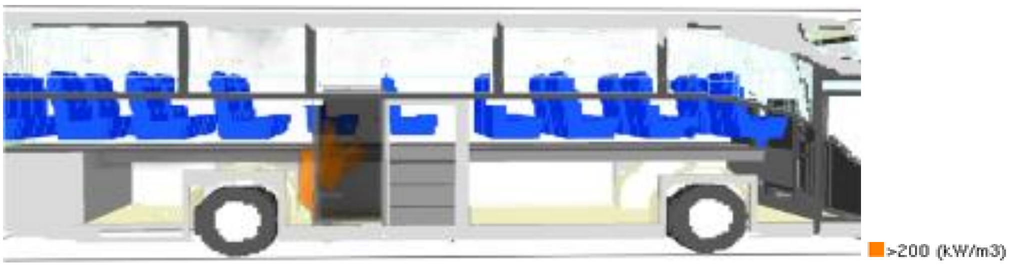


Figure 94 – Fire Spread in the Luggage Compartment in the Hanover Bus Model [69]

In addition to the bus models adopted for the Hanover bus fire scenario so far, also the bus model of a 2012 coach was simulated with the Hanover bus fire scenario. For this bus model the ignition of the lavatory was separately investigated earlier in Chapter 4.2.1.2 since the ventilation aspects of real bus lavatories were additionally considered. In detail the fire penetration from a cable duct at the outside of the lavatory into its interior via a louver was simulated and applied in the Hannover bus fire.

For explaining the ignition and the following fire propagation in the bus stepwise, the sequence of fire development is summarised and commented in Table 36. But the sequence ends already when the passenger cabin is ignited and the flash-over is getting started. This was done since fire development following a flash-over is very similar to those seen in the other scenarios. In particular the fire scenario of an arson attack on passenger seat applied on the bus model of 2012 coach shown in Table 35 is then almost similar related to the flash-over starting there at 2 min elapsed.

Table 36 – Fire Development from Lavatory into Passenger Cabin in Model of a 2012 Coach

| **Fire Development from Lavatory into Passenger Cabin in a 2012 Coach** | |
|---|---|
|  | 00:00<br><br>Before ignition |
|  | 00:15<br><br>Cable duct ignited |
|  | 00:30<br><br>Fire reached lavatory interior |
|  | 01:00<br><br>Fire spread ignites passenger cabin when lavatory door opened |

The overall lesson learned from the Hanover Bus Fire Scenario is that the lavatory can be the source of a very dangerous fire scenario which is able not only to ignite the bus interior within a couple of seconds but finally even the complete bus. In addition this simulation also shows that when it comes to a flash-over then the fire development is very similar over all the different fire scenarios simulated.

#### 4.2.2.3 Engine Compartment ignited

Since most bus fires start in the engine compartment, numerical investigations were focused on this particular location as well. The separation between the engine compartment and the passenger cabin is almost similar across all types of buses modelled. Thus, this scenario was applied on the city bus model only. The most likely way of fire propagation starting in the engine compartment is to penetrate into the passenger compartment. Integrating all combustible parts, all flammable liquids and all possible scenarios would be too complex. Therefore only a simplified engine compartment was used to investigate the main fire conditions in this scenario. In particular the engine compartment modelled consists of a simple cavity in which a heat emitting cuboid is placed as shown in Figure 95. The HRRPUA is set to 125 kW/m². Since lateral areas are able to release heat in this model only, the total heat release of the fire source is 400 kW as conforming to smaller engine compartment fire.

For showing the fire development simulated more clearly the bus model is figured transparent. In Figure 95 the engine compartment modelled is shown from two different points of view as well as in solid and transparent view for comparison.

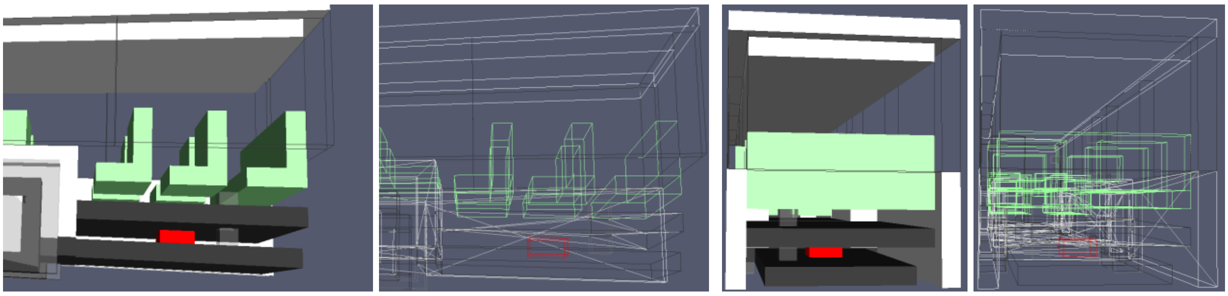
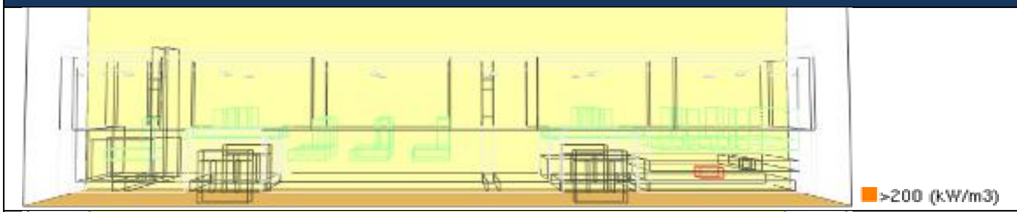
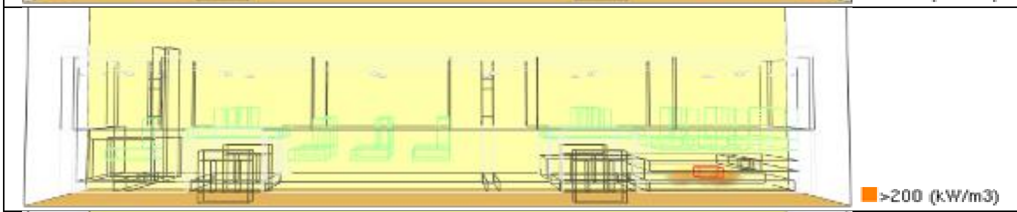
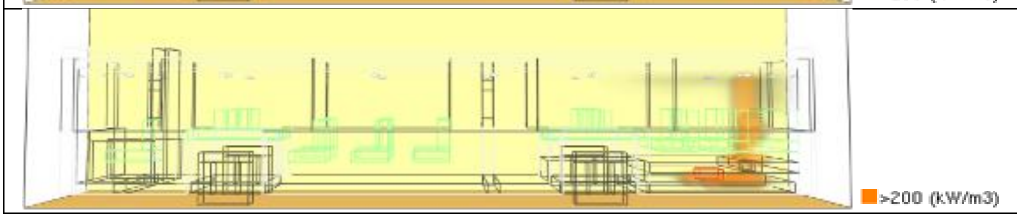
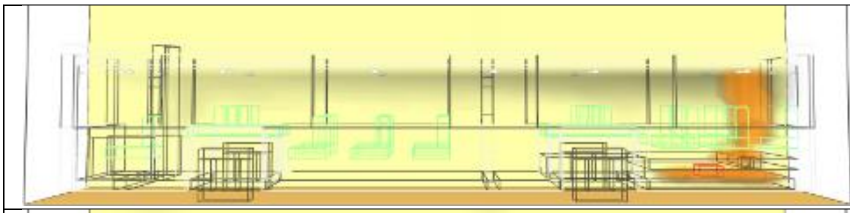
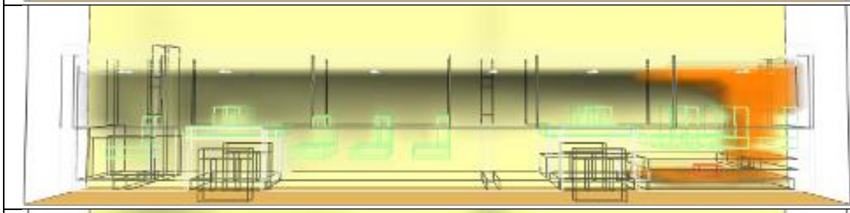
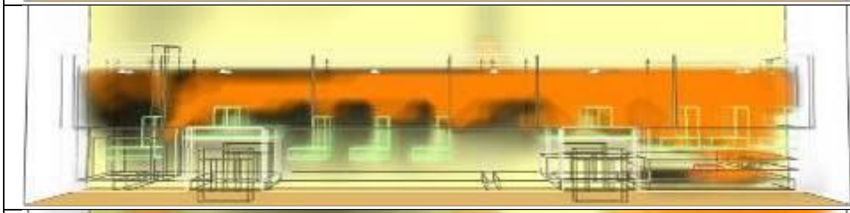
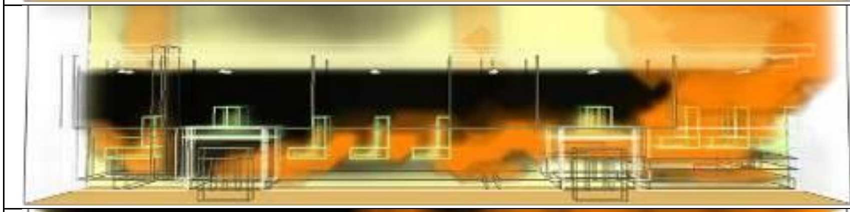
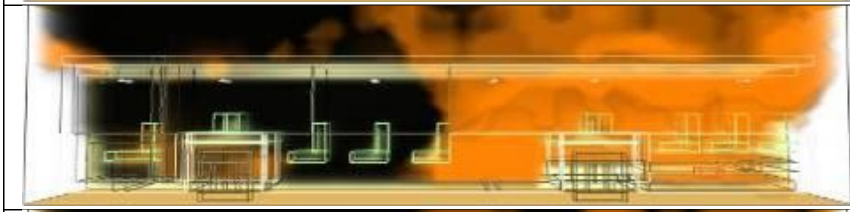
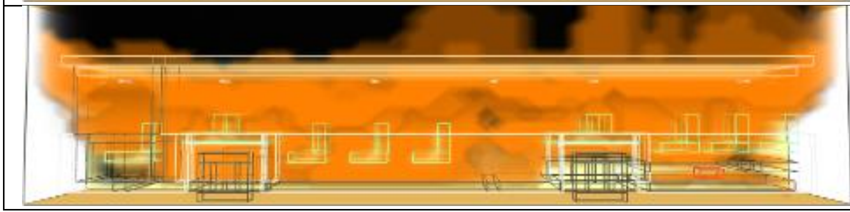


Figure 95 – Engine Compartment Modelled for Getting Ignited in City Bus Model

In this scenario the heat needs to pass the small opening into the passenger cabin first and then to inflame the passenger seat above. For explaining the fire propagation simulated stepwise, the sequence of fire development is summarised and commented in Table 37.

Table 37 – Engine Compartment Fire Simulated in City Bus Model

| Engine Compartment Fire simulated in City Bus Model | |
|---|---|
|   | 00:00<br>Before ignition |
|   | 00:01<br>Engine Fire started |
|   | 00:12<br>Passenger seat ignited |

| | | |
|---|---|---|
|  | >200 (kW/m3) | 00:33<br><br>Seat completely burning and ceiling filled with smoke |
|  | >200 (kW/m3) | 00:36<br><br>Next seat row ignited and flash-over started |
|  | >200 (kW/m3) | 3:30<br><br>Passenger compartment completely burning |
|  | >200 (kW/m3) | 0:48<br><br>Rear window destroyed and fire broken through |
|  | >200 (kW/m3) | 3:50<br><br>Side windows of rear half destroyed |
|  | >200 (kW/m3) | 4:20<br><br>All windows of bus destroyed |

This simulation shows that engine compartment fires can easily ignite parts in the passenger compartment if it comes to a hole in separation between the engine compartment and the passenger cabin. The simulation also proves that seats having a clear distance to the bottom are not protected against such engine compartment fires. Thus, this fire scenario is comparable with passenger seat getting ignited as simulated in Chapter 4.2.2.1. In particular the fire development following the ignition of the passenger seat is almost similar to the one seen in scenarios where the passenger seat is getting ignited.

### 4.2.3 Bus Depot Fire

A fire destroyed the Bottrop bus depot at 25th December 2011 in which 69 city buses from a local public transport were parked inside. This fire was recorded well by a surveillance camera of a petrol station next to the depot showing the fire propagation from depot front and especially the initial fire propagation occurred. Thus, it was established that the source of fire was in the leftmost bus at the bus depot front. Further in fire investigations a battery was identified to be cause of fire. In Figure 96 on the left shows a snapshot of the bus depot when completely burning [72] and the right picture shows burned out buses at next morning. [73]

Figure 96 – Bus Depot Fire near Bottrop in 2011 [72,73]

Since the fire propagation of this bus depot fire was recorded well by the petrol station, a further representative fire scenario for the prepared bus models was available which in addition enabled a direct comparison between fire propagation simulated and the real one.

For this fire scenario the City Bus Model was modified. Features for windows getting destroyed, used so far only for interior surfaces of windows when temperatures exceed a certain value on interior window surfaces, are additionally implemented for the exterior window surfaces. The distances between two buses were set to 40 cm in each direction.

Before simulating the complete bus depot fire scenario, the fire propagation from one bus into the next was investigated. First of all the propagation of fire from a burning bus interior through the back into the adjacent front of the next bus was simulated as summarised in Table 38. The ignition source is based on an engine compartment fire as described in Chapter 4.2.2.3.

Table 38 – Fire Jump from one City Bus into Next

| Fire Jump from one City Bus into Next | |
|---|---|
|   | 00:36<br><br>Flash fire started |
|   | 00:48<br><br>Fire bursts through rear windows |
|   | 01:00<br><br>All rear windows of front bus destroyed |
|   | 01:12<br><br>All windows of front bus destroyed |

| | |
|---|---|
|   | 1:18<br><br>Fire entered second bus through front |
|   | 1:29<br><br>Both buses completely in fire |

Next step for reconstructing the bus depot fire was to simulate the fire propagation of more and more buses in a line. Figure 97 shows the simulation of 12 buses involved in this scenario every time when the next bus interior is getting ignited by fire.

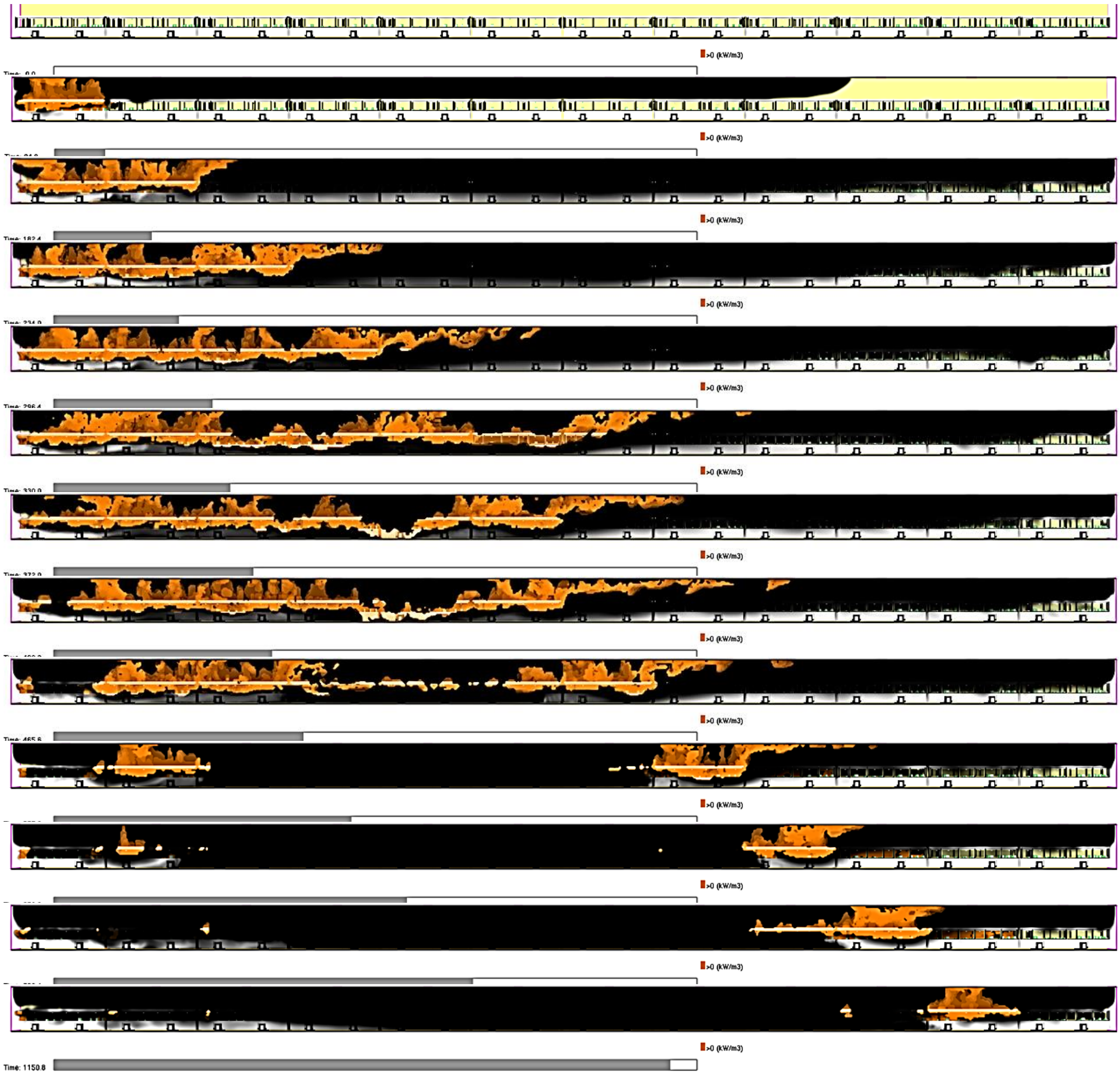
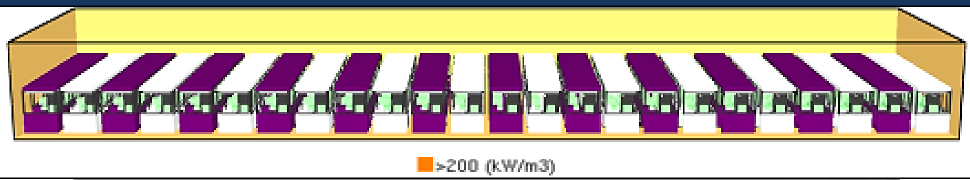
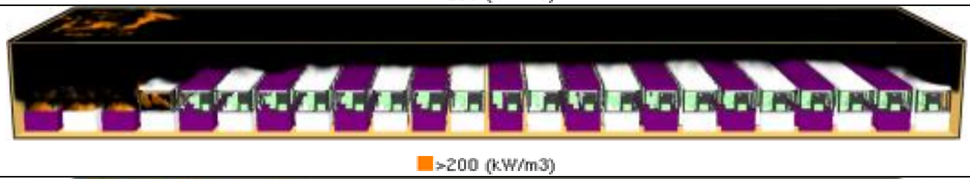
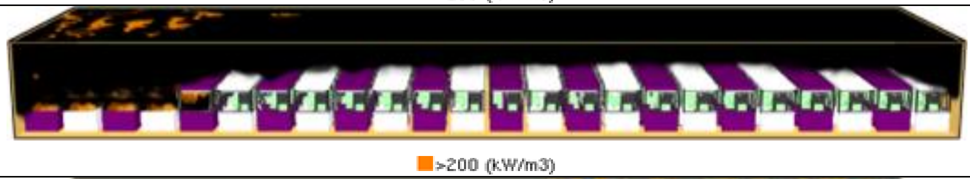
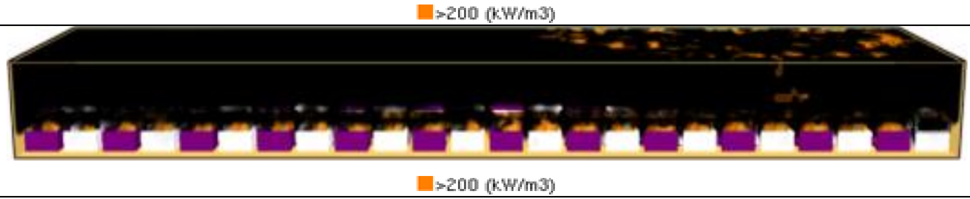



Figure 97 – Simulation of Fire Jump at Adjacent City Buses in a Line

In addition to the fire propagation simulated lengthways the fire propagation crosswise was also investigated in preparation for the complete bus depot fire simulation. In the beginning two adjacent buses and afterwards a row of 10 buses was simulated. Since the survey report of the Bottrop's bus depot fire was available for the dissertation at hand, detailed information about the bus depot could be established. In particular it states that 24 buses could be parked parallel in the depot and that the front doors of all stored buses were open. Therefore a row of 24 adjacent buses with an open front was simulated.

In the beginning the fire propagation in the next bus took a while, however, thereafter the fire entered the next bus approximately every 30 to 35 s. Table 39 shows a summary of this simulation.

Table 39 – Simulation of Fire Propagation Crosswise from one City Bus into Next

| **Simulation of Fire Propagation Crosswise from One City Bus into Next** | |
|---|---|
|   | 00:00<br><br>Fire commencing |
|   | 01:21<br><br>Fire propagated into $2^{nd}$ bus |
|   | 01:54<br><br>Fire propagated into $3^{rd}$ bus |
|   | 02:26<br><br>Fire propagated into $4^{th}$ bus |
|   | 2:59<br><br>Fire propagated into $5^{th}$ bus |
|   | 13:41<br><br>Fire propagated into $24^{th}$ bus |

With the results gained in the fire propagation investigations the full Bottrop depot fire was modelled. Since detailed information of the Bottrop bus depot were not available in the beginning a fictional scenario based on a big bus depot containing 15 by 12 buses was simulated first as shown in Figure 98. The bus hall was modelled with opened skylights as indicated by purple rectangles in Figure 98 to implement the smoke and heat extraction system usually installed in such bus depots. There is one skylight located centred above each bus.

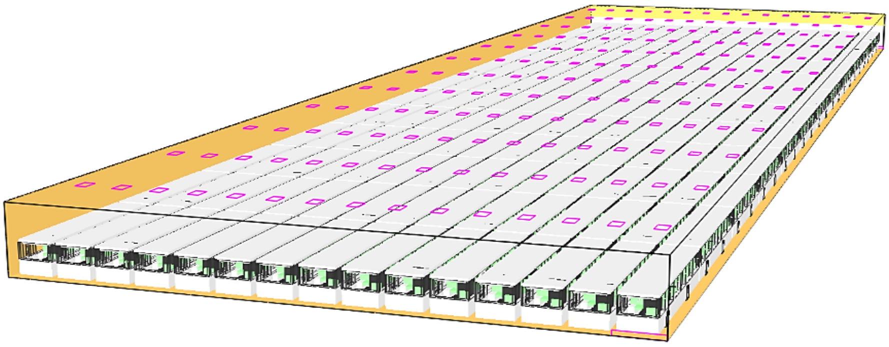


Figure 98 – Simulation of huge Bus Depot

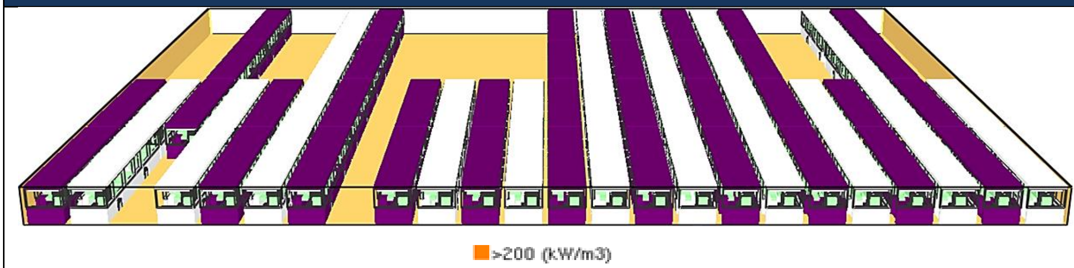
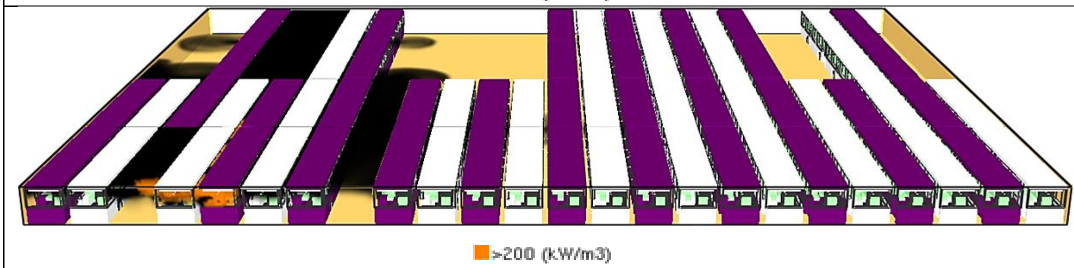
Results of this simulation could show that in such a uniform pattern of buses the fire propagates wavelike. However, the fire propagation crosswise proceeds faster than then lengthwise. Reason for this effect is that there is larger window front at the bus sides than at the bus back or front.

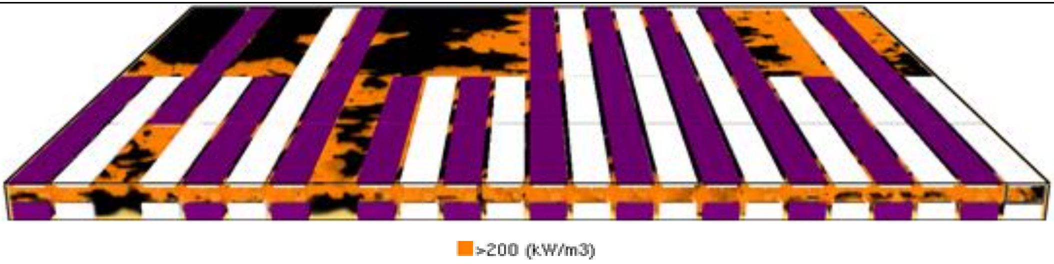
As soon as the survey report was available, further details as the locations of the 69 buses involved and the location of the fire source were implemented in the Bottrop bus depot model. The fire propagation of this simulation is shown and commented in Table 40. In contrast to the fictional bus depot simulation outlined in Figure 98 the feature for window getting destroyed was extended by a FDS function delaying 60 s since the fire propagation simulated was quicker than recorded by surveillance camera in the real bus depot fire.

The dimension of the bus depot modelled are 67.60 m in length resulting from 24 buses in parallel plus 0.4 m space around each bus, 50.00 m in width resulting from 4 buses in row plus 0.4 m space around and 4.00 m in height resulting from height of usual city bus plus 1.00 m space above. Since the cell grid is set to 0.20 m boxes, there are 1,690,000 cells involved in total. Openings available in the bus hall are implemented in the Bottrop bus depot model in order to consider the ventilation condition. In particular an open front and rear as well as one skylight above each parking lot were set.

Since there is a gap in the vehicle distribution between the left and the right bundles of buses, the focus is set on how the fire propagation takes place there.

Table 40 – Simulation of Complete Bottrop Bus Depot Fire

| **Simulation of Complete Bottrop Bus Depot Fire** | |
|---|---|
|   | 00:00<br><br>Fire commencing |
|   | 02:02<br><br>Fire propagated into next bus |

| | |
|---|---|
|  | 07:05<br><br>Fire propagated into 3rd bus |
|  | 23:53<br><br>All buses burning |

In conclusion this simulation gives validation for the material data applied since the fire propagation following is clearly recorded by the surveillance camera. However, the recordings are generally suitable for rough assessments at the bus depot front only. Effects, such as the roof collapse occurred and bus depot equipment involved other than buses, are not implemented in this simulation at all. Finally the simulation of the Bottrop bus depot fire was running a bit faster than the real Bottrop bus depot fire seen. Nevertheless, the Bottrop bus depot fire simulation reproduced the fire development recorded almost realistically.

# 5. Conclusions

The dissertation at hand is completed by a summary and a final conclusion. In addition insights gained during the work are summarised in lessons learned.

## 5.1 Summary

Basic questions of the dissertation at hand was, what is the status quo of fire safety in road vehicles and how can it be reasonably assessed? To find answers for these questions, research was done to develop '..a combined experimental and simulative method for the assessment of fire scenarios in motor vehicles' related to the dissertation at hand.

From standardization perspective the fire safety of road vehicles is a neglected area in recent decades and have not been adjusted to modern materials being robust, lightweight and cost-efficient. Due to carrying a lot of passengers who would be seriously endangered in case of fire, buses are particularly focused at. Thus, typical interior materials of current bus series were selected for testing. In ATR tests performed these samples have proven that all material tested were made of plastic which are generally able to burn due to their organic molecules.

To establish the fire behaviour of these materials based on a reliable and transparent method, a couple of common fire tests used in material science were performed. Same fire tests are usually required for limiting fire characteristics of interior materials in most other transport means such as for rail vehicles but not for road vehicles although operation conditions of road and rail vehicles are comparable. While doing so, cone calorimeter tests have shown that bus interior materials are quite easy to ignite when heat radiation is affecting and in particular that they release high amount of heat and smoke while burning. Furthermore tests in the smoke density chamber have proven that these materials release vast amounts of opaque smoke containing high concentrations of toxic gases. For most samples lethal smoke gas concentrations were reached within a point in time in which the evacuation of passengers would probably be still ongoing. In addition single flame source tests have indicated that materials tested can be quickly and easily ignited by a small flame being comparable with a lighter. Furthermore an almost unhindered fire propagation in vertical direction is then arising. To complete results from small-scale fire tests additional real-scale fire tests were run with separate interior parts. This was mainly done to investigate the fire safety performance of parts which are essential for fire propagation due to their quantity and dimensions in interior. For instance passenger seats of different bus types were tested and compared with those from trains. Newspaper crumpled-up and inflamed for simulating a simple arson attack was able to easily ignite the bus passenger seats which then were releasing extreme amounts of heat and smoke while burning.

Due to the poor fire behaviour of interior materials established, several fire detectors and fire suppression systems specialised for buses were examined in fire tests performed in a real bus to assess the application of alternative compensation measures. On one side smoke spread tests were performed in the passenger compartment for investigating different fire detectors there. These tests have shown that in case of fire passenger compartments are completely filled with smoke quickly, even when smaller fire scenarios were applied. However, smoke detectors installed at the ceiling of the passenger compartment were able to promptly alarm fire. On the other side fire tests were performed in the engine compartment of a real bus to examine systems for fire detection and fire suppression which are specialised for combustion engine compartments. Most common fire scenarios were promptly suppressed. In case of highly challenging scenarios the fire there was interrupted at least for a safe evacuation moment. However, fire detectors delivered different results there. Some of those alarmed exceedingly reliable but some few not at all.

Beside of fire tests, numerical fire simulations were run with different bus models to investigate the fire propagation within full-scale bus interiors. By doing so, material properties from typical bus interior parts gained in specific material fire tests were applied. Fire scenarios simulated represent arson attacks and technical defects, such as a source of fire at a passenger seat, in a lavatory, in the luggage compartment and in the engine compartment. In addition the Hannover bus fire and the Bottrop bus depot fire were reconstructed based on survey reports. Finally these numerical simulations could demonstrate to be a meaningful completion for the overall fire performance assessment of road vehicles without performing complex fire tests with entire vehicles.

## 5.2 Final Conclusion

The dissertation at hand could show how complex it is to assess fire scenarios in road vehicles and that a combined experimental and simulative method can be used as a reasonable approach to get adequate results. Small geometries and a limited amount of possible fire tests narrow the application of well-established fire safety concept procedures, such as from e.g. building sector, industrial facilities or from other transport means. Thus, the approach based on small scale material tests and some few real-scale fire tests with crucial parts finally combined with well-prepared numerical fire simulations is a proper and well-applicable method for assessing fire performance of motor vehicles.

Beside this, the fundamental research work of the dissertation at hand has additionally disclosed that road vehicles provide generally a poor fire safety performance due to weak requirements of interior materials. This especially pertains to buses due to their capabilities to carry many passengers within a small space. In addition investigations with systems for fire suppression and fire detection specialised for application in buses has come to the conclusion that these system are absolutely advisable enhancements for passenger safety. However, they cannot compensate the fire performance shortcomings of interior materials.

## 5.3 Lessons Learned

The dissertation at hand covers results from researching, testing and simulating regarding fire safety of road vehicles in which new experiences have been made, several lessons have been learned and some best praxis methods have been established.

### 5.3.1 Typical Sources of Fire in Road Vehicles

When assessing the status of fire safety performance regarding road vehicles, typical sources of fire were analysed first. These can be simply categorised into mechanical and/or electrical defects or arson attacks. Mechanical defects causing fire are usually malfunctions of parts or materials such as material fatigues, blockages and/or leakages. The ignition process following is then almost similar since parts run hot or parts with damaged heat protections ignites combustible materials nearby. This usually occurs in driving units and especially in engine compartments which contain most of rotating parts and several hot surfaces as well as combustible liquids as fuel and lubricants in a tight space. Thus, this is the most likely area causing fire in road vehicles. Following this, vehicle fires as a result of a crash can be classified as caused in consequence of mechanical malfunction as well.

Electrical defects are malfunctions of electrical components such as overheating or arcing following mechanical defects or material fatigue in electrical equipment. In case of overheating the ignition process is similar to those described for overheating due to mechanical malfunctions. In contrast arcs directly ignite combustible materials or liquids due to their electrical power. However, when occurring, electrical defects are not concentrated to the engine compartment only since they have been caused fires everywhere along the electrical installations through the entire vehicles.

Beside fires following mechanical or electrical defects, fires can also be caused by arson attacks inside and outside the vehicle. In case of operating buses carrying passengers they have been most commonly occurring in the passenger compartment.

Measures preventing these typical fire sources are generally implemented by regular maintenance intervals and actively monitoring the passengers by driver or staff. However, the risk of such fire sources cannot be neglected at all. Thus, the fire performance of materials applied should be adequately enhanced.

### 5.3.2 Fire Performance of Interior Materials from Road Vehicles

Fire tests and simulations performed for the dissertation at hand state a clearly poor fire safety performance of materials applied in road vehicles. These are usually plastic materials providing worse reaction-to-fire performance although being compliant to fire safety standards required. Especially ignitability, release of heat and smoke as well as fire propagation and smoke gas toxicity are issues of the fire behaviour road vehicles. The fire safety here has been a neglected area in recent decades and have not been adjusted to modern materials being robust, lightweight and cost-efficient yet.

A fire test series investigating the fire behaviour of different types of passenger seats from buses and trains as well as a driver seat from a car have shown that the seats from road vehicles can be easily ignited already by simple arson attacks with newspaper crumpled-up. Then when burning, they release extreme amounts of heat and smoke. In contrast passenger seats conforming to rail standards provide adequate fire protection since they were not ignited by this arson attack scenario due to their strict fire behaviour requirements.

While working on the dissertation at hand few enhancements regarding fire behaviour of bus interior materials have been done probably as a consequence of interim results presented in corresponding conferences and working groups of regulators:

- ’Materials installed in a vertical position in the interior compartment, in the engine compartment and any separate heating compartment shall pass a vertical fire test‘ (Section 6.2.5 of UNECE R 118 [26])
- ’Insulation materials installed in the engine compartment and any separate heating compartment shall succeed a test determining the capability of materials to repel fuel or lubricant‘ (Section 6.2.3 of UNECE R 118 [26])
- ’Materials achieving an average CFE (critical heat flux at extinguishment) value greater or equal to 20 kW/m², when tested according to ISO 5658-2 3, are deemed to comply with the requirements‘ (Section 6.2.4 of UNECE R 118 [26])
- ’Vehicles shall be equipped with an alarm system detecting either an excess temperature or smoke in toilet compartments, driver's sleeping compartments and other separate compartments. Upon detection, the system shall provide the driver with both an acoustic and a visual signal in the driver's compartment. The alarm system shall be at least operational whenever the engine start device is operated, until such time as the engine stop device is operated, regardless of the vehicle's attitude‘ (Section 7.5.6 of UNECE R 107 [29])
- ’In addition to the alarm system, vehicles of Classes I, II and III shall be equipped with a fire suppression system in the engine compartment and each compartment where a combustion heater is located. Vehicles of Classes A and B, may be equipped with a fire suppression system in the engine compartment and in each compartment where a combustion heater is located.’ (Annex 3, Paragraph 7.5.1.5 of UNECE R 107 Revision 6 - Amendment 5 [74])

Finally avoiding combustible materials would lead to best fire safety results. However, comfort and quality demands from costumers are making this impossible. Thus, preventing ignitions, limiting the release of heat and smoke as well as avoiding toxicity and mitigating fire propagation must be fundamentals of adequate fire safety deliverables. This can be easily transferred from part 2 of EN 45545 [26] which is the current fire safety standard for materials applied in rail vehicles. Thinking further ahead, adopting the entire EN 45545 requirements is highly recommended since it contains all the important fire aspects and adequate limits which should be addressed for fire safety of road vehicles as well, especially for those carrying many passengers as buses:

- EN 45545 part 1: General [75]
- EN 45545 part 2: Requirements for fire behaviour of material and components [34]
- EN 45545 part 3: Fire resistance requirements for fire barriers [76]
- EN 45545 part 4: Requirements for rolling stock design [77]
- EN 45545 part 5: Fire safety requirements for electrical equipment.. [78]
- EN 45545 part 6: Fire control and management systems [79]
- EN 45545 part 7: Fire safety requirements for flammable liquid and gas installations [80]

### 5.3.3 Measures enhancing Fire Safety Performance

Due to the poor fire performance in road vehicles additional fire tests were performed with automatic fire detection and fire extinguishing systems to examine their capability of compensating fire performance issues of current material requirements in buses. On one side smoke spread tests performed in the passenger compartment of a real bus investigating fire detectors and their appropriate locations there have shown that passenger compartments are quickly completely filled with opaque smoke, even in case of small parts burning. Smoke detectors installed at the ceiling of the passenger cabin provided an early and reliable alarm in these test scenarios as well as while fire tests in the engine compartment with motor running when a lot of smoke penetrated into the passenger compartment. In addition opened skylights and trap windows reasonably supports reducing smoke since smoke can stream out there. In doing so, the area below this level of height is then almost clear of smoke due to the buoyancy effect of hot gases.

On the other side fire tests in the engine compartment of real buses and in appropriate fire test rigs were performed with different fire scenarios possible and based on different agents and/or suppression methods. Results have proven that specialised fire suppression systems with specific approaches and technologies for engine compartments can promptly stop the fire in an engine compartment. In some few cases when applying highly challenging fire scenarios the fires were at least interrupted for a moment affording a safe evacuation. However, fire suppression can principally not compensate the worse reaction-to-fire behaviour of interior materials applied but is a meaningful approach enhancing passenger safety in road vehicles wherefore it is implemented in last amendment for bus requirements [74].

Fire detectors were additionally examined in the preheating phase of the fire suppression tests in the engine compartment. The results have proven that in particular linear heat detectors with an adequate alarm level provide quick and reliable fire alarms for engine bays when installed well distributed while spot detectors based on bimetallic switch and smoke detectors failed throughout in same tests.

In conclusion appropriate systems for fire detection in passenger compartments and further in separated compartments as well as specialised fire detection and suppression systems for engine compartments are available on the market. The accuracy of fire detection systems is not explicitly required by standards yet. In contrast the performance of fire suppression systems is going to be ensured by corresponding fire suppression tests based on representative scenarios for those systems becoming effective with next revision of standards. But although implementing these systems is highly recommended especially in road vehicles carrying many passengers such as buses, these systems can principally not compensate the worse reaction-to-fire behaviour of materials being applied in road vehicles.

### 5.3.4 Numerical Fire Simulation

For the dissertation at hand several numerical fire simulations were run to get findings for full scale-fire scenarios based on material fire tests performed. These results state that this approach was successful and has gained adequate results as those probably obtained in real fire tests. In addition this method has saved a lot of efforts and costs in performing real-scale fire tests.

Fire scenarios run are complying with most common fire scenarios. On one side arson attacks on passenger seats were simulated across several types of buses and on the other side engine compartment fires were run. In addition a scenario reconstructing the Hannover bus fire was modelled in which the complex fire propagation scenario occurred could be simulated.

Since the overall fire performance of buses examined is as bad as assumed from small-scale fire tests, those fire simulations were repeated with interior materials conforming to rail material requirements. By doing so the fire safety performance was appreciably enhanced due to more stringent fire requirements.

In the environment of an engine compartment test rig according to SP-Method 4912 the simulation of fire suppression was tried but hasn't come to reliable results. However, these simulations have proven that the ventilation conditions are challenging while suppressing fires. In particular there are compartment areas with strong and also with low airflow each test scenario of SP-Method 4912.

In addition to simulations investigating single bus parts or an entire bus a bus depot fire occurred 2011 in Bottrop was reconstructed. It could be shown that the fire propagation simulated based on material data implemented in FDS models is mostly similar to those seen in real-scale fire tests. However, in the bus depot fire simulation this comparison was investigated across several buses.

Finally the simulations performed have shown that the fire simulation program applied, which was developed for fire scenarios in buildings, is also able to simulate such complex and detailed fire models. However, more modern CFD simulation programs are available on the market meanwhile which are able to simulate such fire simulation more exact. However, these would need additional efforts for modelling these scenarios too.

Fire simulations performed within bus models applied have shown that the fire behaviour following flash-over in the passenger cabin is almost similar, even across different bus models. However, the fire development until the flash-over occurs is different in various fire scenarios and therefore of interest when simulating several scenarios. Using this can save a lot of calculation time.

Since such fire simulations have been successfully run for buses, it can be assumed that reliable results are also possible for all other types of road vehicles as long as representative sampling of materials has been analysed for this and as the condition, such as ventilation, is implemented in the simulation model.

In conclusion these fire simulations point out that numerical simulation are able to complete fire performance assessments without several expensive full-scale tests.

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# Annex I – Main Combustion-relevant Terms related to this Work

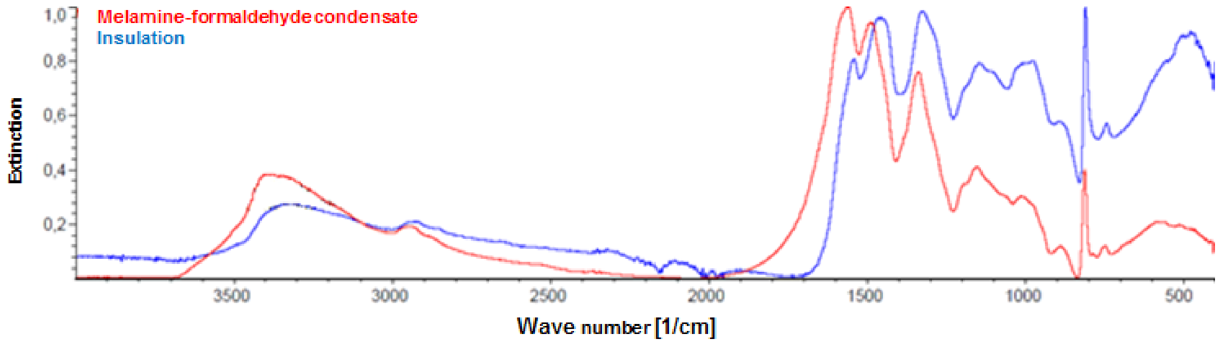
| Main Combustion-relevant Terms of DIN EN ISO 13943 [1] | |
|---|---|
| Burn | Undergo combustion |
| Char | Carbonaceous residue resulting from pyrolysis or incomplete combustion |
| Combustion | Exothermic reaction of a substance with an oxidizing agent |
| Combustible | Capable of being ignited and burned |
| Combustion product | Solid, liquid and gaseous material resulting from combustion |
| Fire (general) | Process of combustion characterized by the emission of heat and fire effluent and usually accompanied by smoke, flame, glowing or a combination thereof |
| Fire (controlled) | Self-supporting combustion that has been deliberately arranged to provide useful effects and is limited in its extent in time and space |
| Fire (uncontrolled) | Self-supporting combustion that has not been deliberately arranged to provide useful effects and is not limited in its extent in time and space |
| Fire behaviour | Change in, or maintenance of, the physical and/ or chemical properties of an item and/ or structure exposed to fire |
| Fire effluent | Totality of gases and aerosols, including suspended particles, created by combustion or pyrolysis in a fire |
| Fire gases | Gaseous part of combustion product(s) |
| Fire load | Quantity of heat which could be released by the complete combustion of all the combustible materials in a volume, including the facings of all bounding surfaces |
| Fire resistance | Ability of a test specimen to withstand fire or give protection from it for a period of time |
| Fire retardant | Substance added, or a treatment applied, to a material in order to delay ignition or to reduce the rate of combustion |
| Fire scenario | Qualitative description of the course of a fire with respect to time, identifying key events that characterize the studied fire and differentiate it from other possible fires |
| Fire test | Test that measures behaviour of a fire or exposes an item to the effects of a fire |
| Flame | Rapid, self-sustaining, sub-sonic propagation of combustion in a gaseous medium, usually with emission of light |
| Flame retardant | Substance added, or a treatment applied, to a material in order to suppress or delay the appearance of a flame and/ or reduce the flame-spread rate |
| Flame spread | Propagation of a flame front |
| Flaming combustion | Combustion in the gaseous phase, usually with emission of light |
| Flaming debris | Material separating from a burning item and continuing to flame during a fire or fire test |
| Flammability | Ability of a material or product to burn with a flame under specified conditions |
| Flashover | Transition to a state of total surface involvement in a fire of combustible materials within an enclosure |
| Fuel | Substance that can react exothermically with an oxidizing agent |
| Glowing | Luminosity caused by heat |
| Heat flux | Amount of thermal energy emitted, transmitted or received per unit area and unit time |
| Heat of combustion | Thermal energy produced by combustion of unit mass of a given substance |
| Heat release | Thermal energy produced by combustion |
| Heat release rate | Rate of thermal energy production generated by combustion |
| Heat stress | Conditions caused by exposure to elevated or reduced temperature, radiant heat, or a combination of these factors |
| Ignitability | Measure of the ease with which a test specimen can be ignited, under specified conditions |
| Ignite | Catch fire with or without the application of an external heat source |
| Ignition | Initiation of combustion |
| Ignition source | Source of energy that initiates combustion |

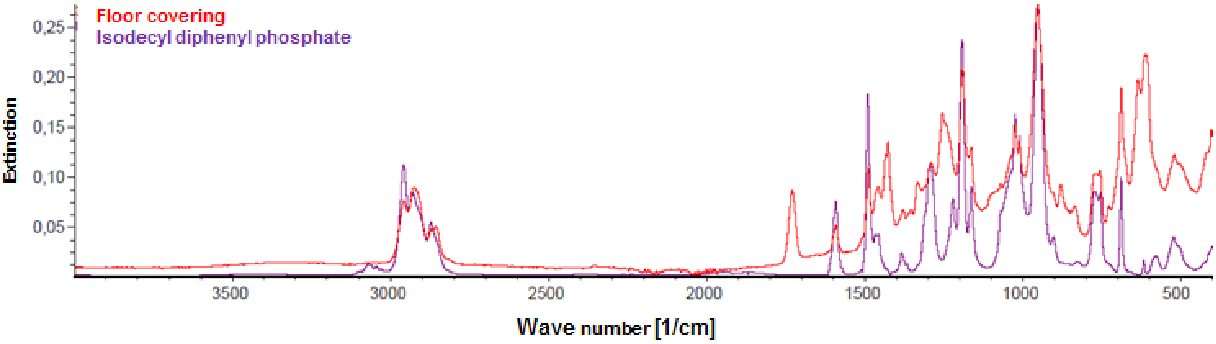
| | |
|---|---|
| Large-scale test | Fire test, that cannot be carried out in a typical laboratory chamber, performed on a test specimen of large dimensions |
| Mass loss rate | Test specimen mass loss per unit time under specified conditions |
| Melting behaviour | Phenomena accompanying the liquefaction of a material under the influence of heat |
| Non-combustible | Not capable of undergoing combustion under specified conditions |
| Non-flammable | Not capable of burning with a flame under specified conditions |
| Numerical fire model | Mathematical representation of one or more of different interconnected phenomena governing the development of a fire |
| Opacity of smoke | Ratio of incident light intensity to transmitted light intensity through smoke, under specified conditions |
| Optical density of smoke | Measure of the attenuation of a light beam passing through smoke expressed as the logarithm to the base 10 of the opacity of smoke |
| Oxidation | Chemical reaction in which the proportion of oxygen or other electronegative element in a substance is increased |
| Oxidizing agent | Substance capable of causing oxidation |
| Pyrolysis | Chemical decomposition of a substance by the action of heat |
| Reaction to fire | Response of a test specimen when it is exposed to fire under specified conditions in a fire test |
| Real-scale fire test | Fire test that simulates a given application, taking into account the real scale, the real way the item is installed and used, and the environment |
| Self-extinguish | Cease combustion without being affected by any external agent |
| Small-scale fire test | Fire test performed on a test specimen of small dimensions |
| Smoke | Visible part of fire effluent |
| Smoke production | Amount of smoke that is produced in a fire or fire test |
| Smouldering | Combustion of a material without flame and without light being visible |
| Soot | Particulate matter produced and deposited during or after combustion |
| Spectroscopy | Study of spectra, especially to determine the chemical composition of substances and the physical properties of atoms, molecules, and ions |
| Test specimen | Item subjected to a procedure of assessment or measurement |
| Thermal radiation | Transfer of thermal energy by electromagnetic waves |
| Toxicity | Ability of a substance to produce adverse effects upon a living organism |

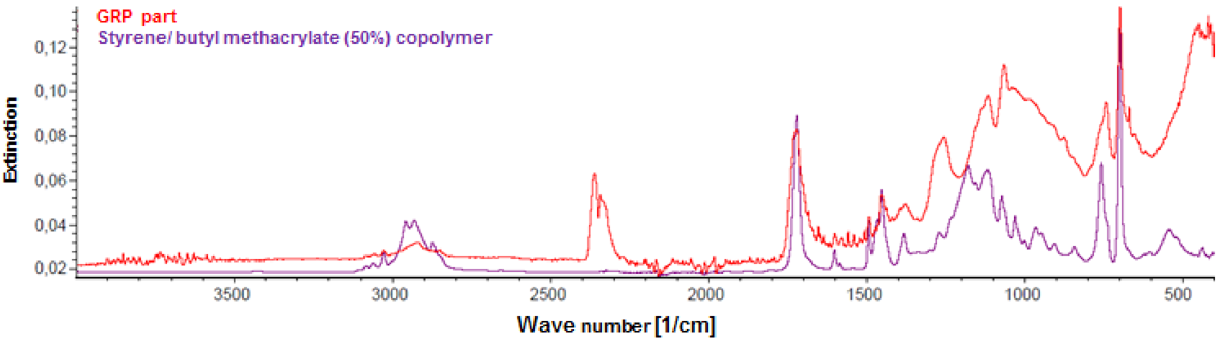
# Annex II – Fire Safety Regulations for Buses in Germany

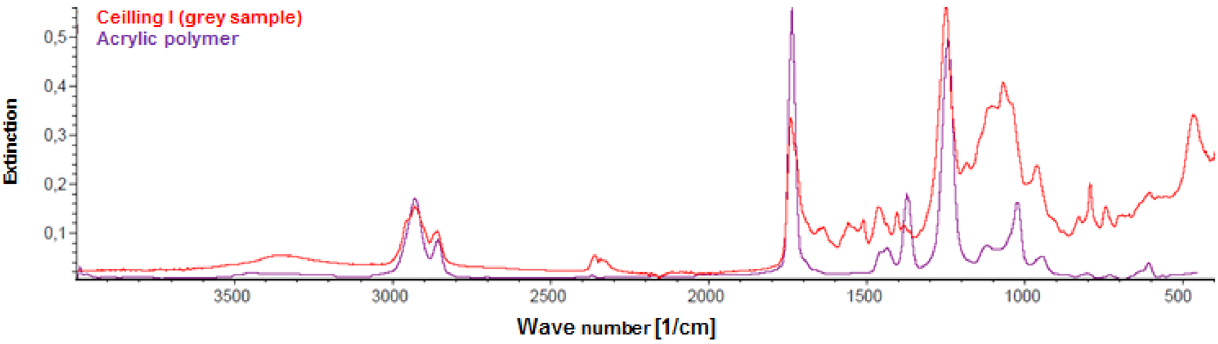
| Current Fire Safety Regulations for Buses in Germany [25 – 30] | |
|---|---|
| StVZO §35g | Fire extinguisher in autobuses |
| StVZO §35j | Burning behaviour of interior of certain buses |
| StVZO §45 | Fuel container |
| StVZO §46 | Fuel feed pipe |
| 95/28/EC | Burning behaviour of materials used in interior construction of certain categories of motor vehicles |
| 2000/8/EC | Liquid fuel tanks and rear underrun protection of motor vehicles and their trailers |
| 2001/85/EC | Special provisions for vehicles used for the carriage of passengers comprising more than eight seats in addition to the driver's seat |
| ECE-R 36 | Uniform provisions concerning the approval of large passenger vehicles with regard to their general construction (incl. fire extinguisher, fuel container and fuel feed pipe) |
| ECE-R 107 | Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction (incl. fire extinguisher, engine compartment and allowed materials in the engine compartment, heat sources, electricity) |
| ECE-R 118 | Uniform technical prescriptions concerning the burning behaviour of materials used in the interior construction of certain categories of motor vehicles |

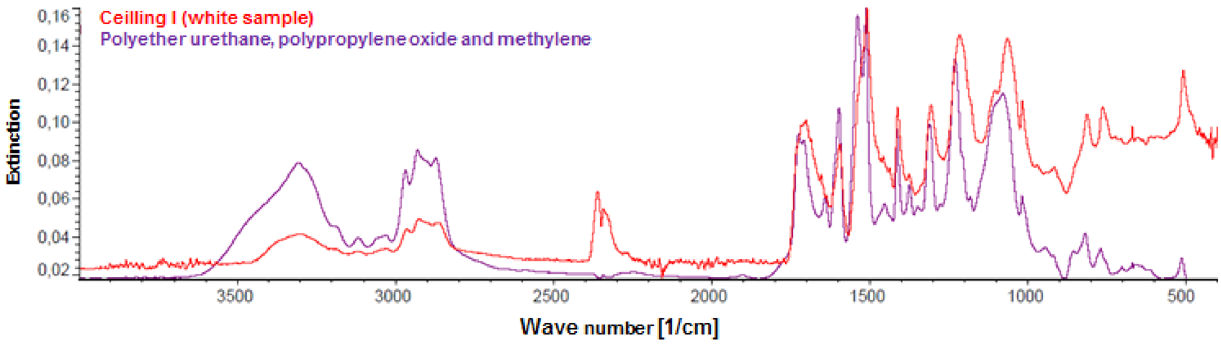
# Annex III – Material Curves of ATR Spectroscopy

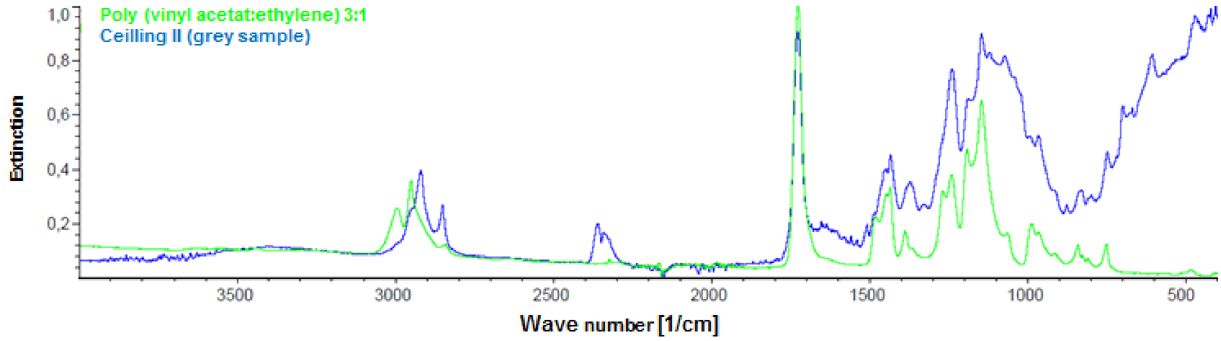


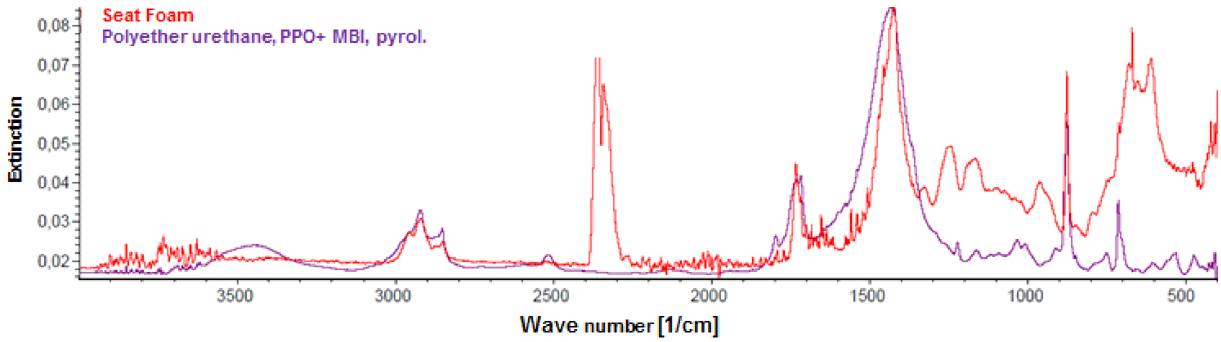



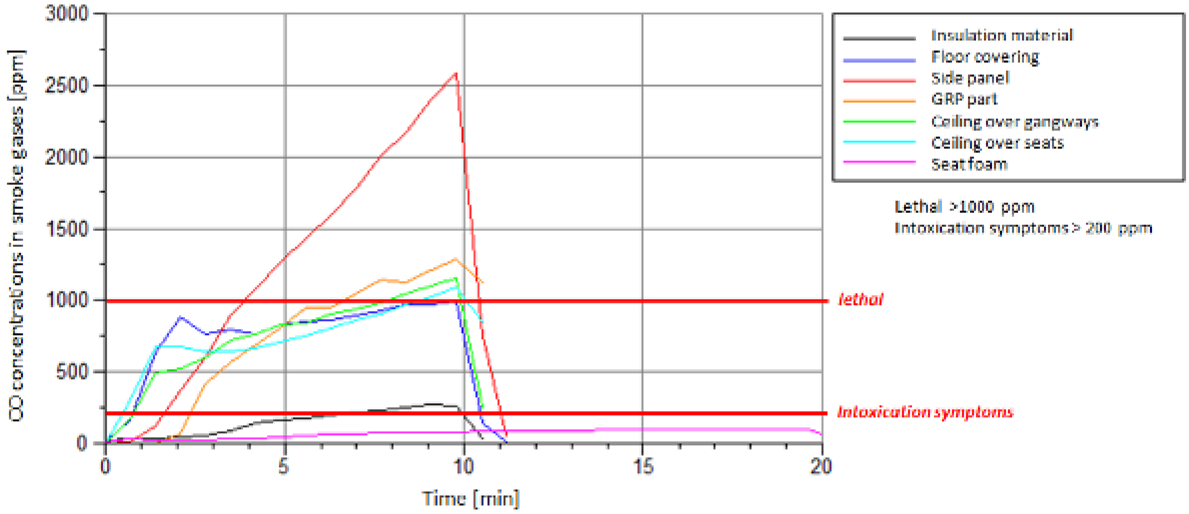



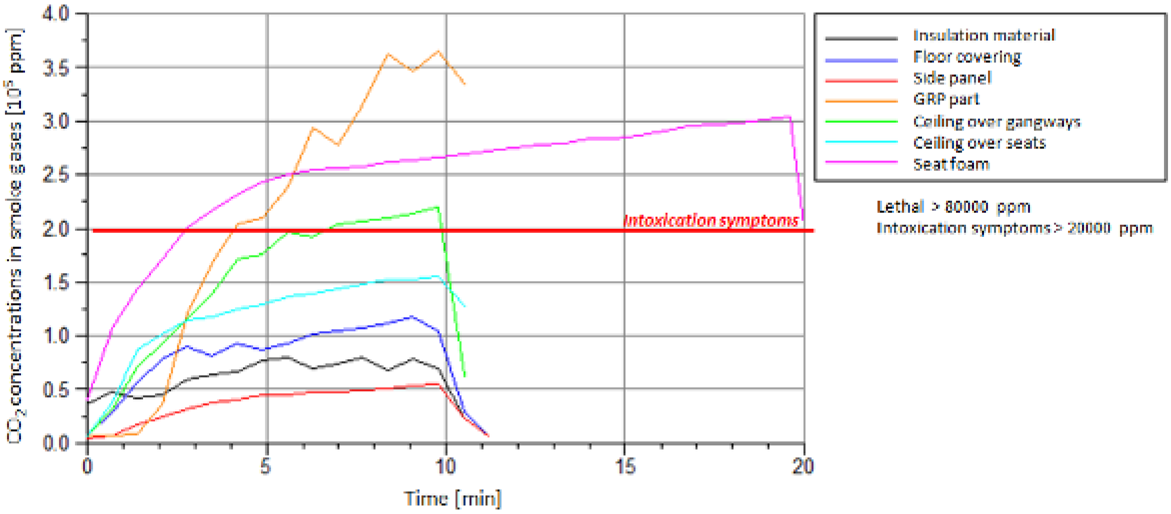

Ceilling I (white sample)
Polyether urethane, polypropylene oxide and methylene
Extinction
0,16
0,14
0,12
0,10
0,08
0,06
0,04
0,02
3500
3000
2500
2000
1500
1000
500
Wave number [1/cm]

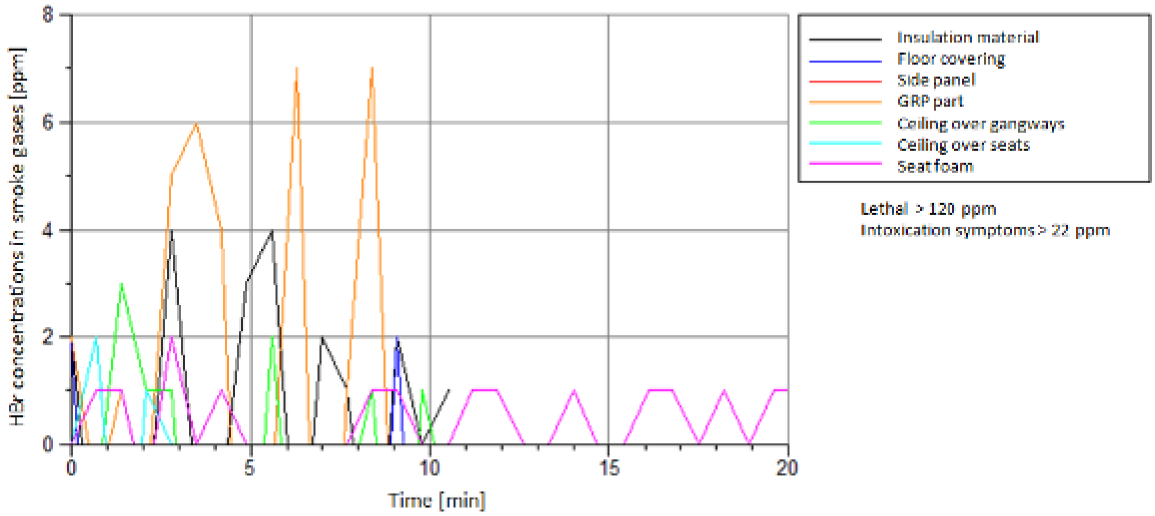

Poly (vinyl acetat:ethylene) 3:1
Ceilling II (grey sample)
Extinction
1,0
0,8
0,6
0,4
0,2
3500
3000
2500
2000
1500
1000
500
Wave number [1/cm]

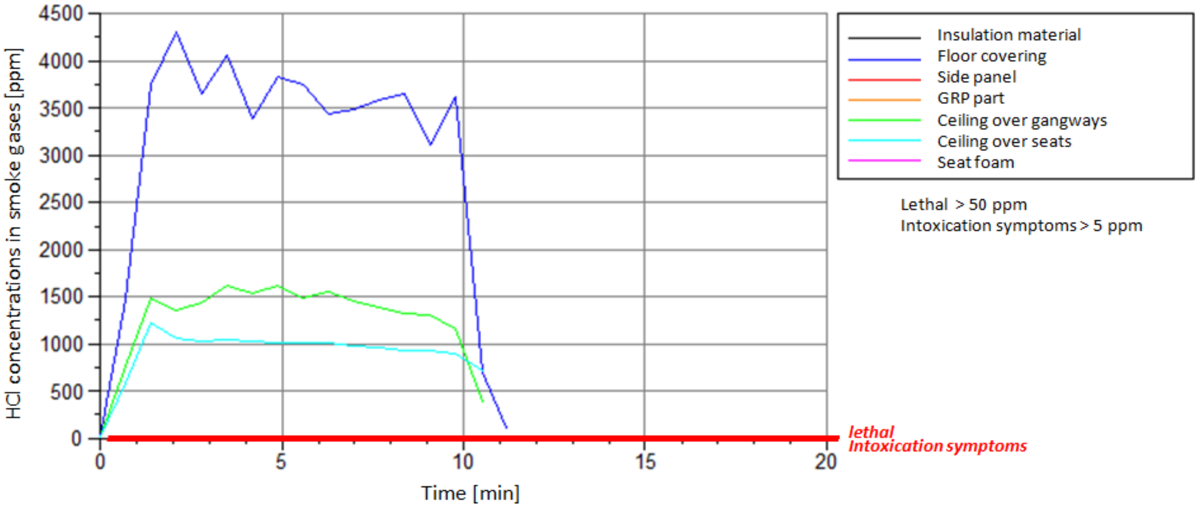

Seat Foam
Polyether urethane, PPO+ MBI, pyrol.
Extinction
0,08
0,07
0,06
0,05
0,04
0,03
0,02
3500
3000
2500
2000
1500
1000
500
Wave number [1/cm]

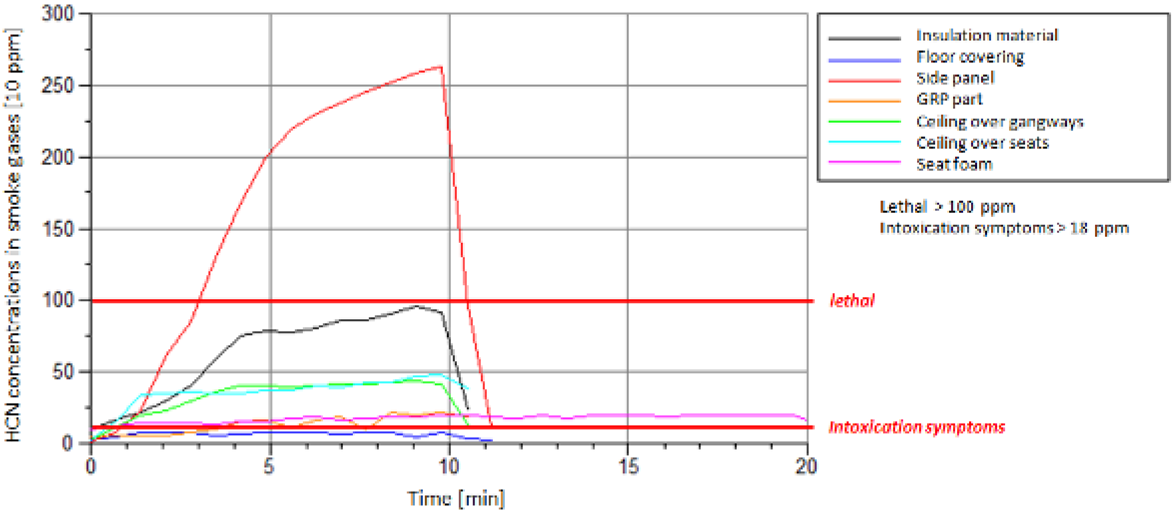
# Annex IV – Concentrations of Toxic Smoke Gas Components

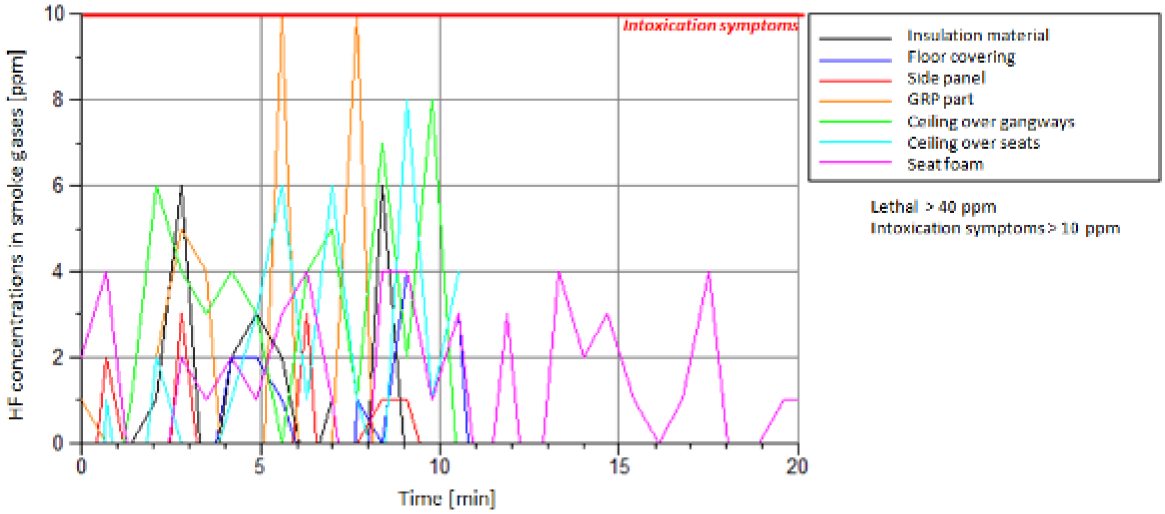


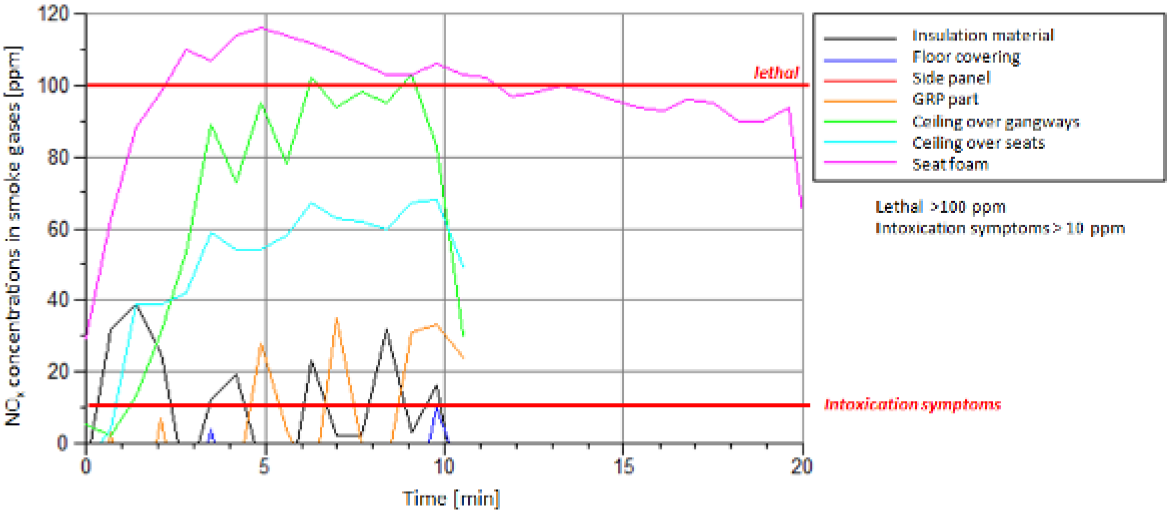



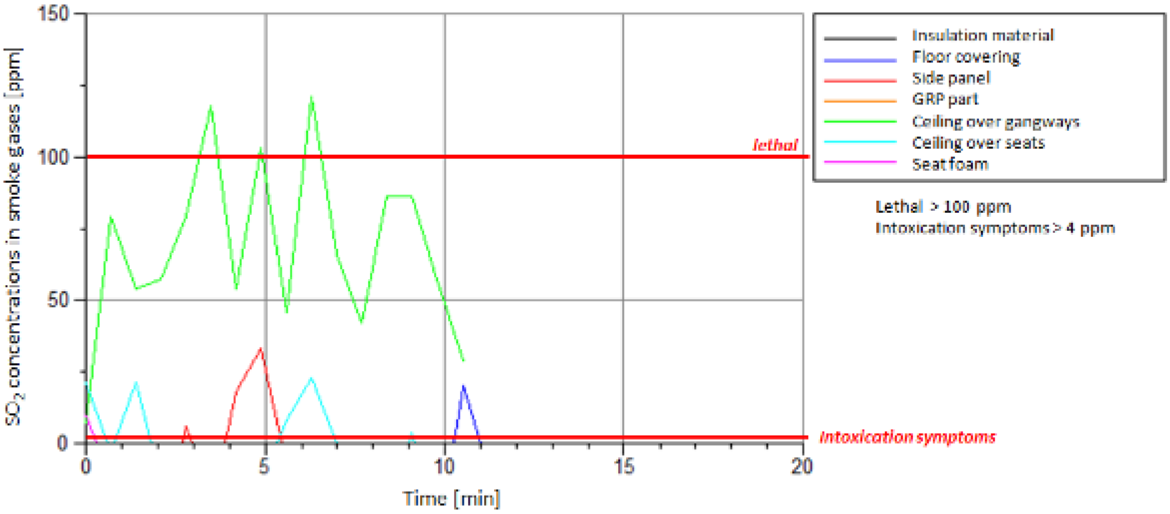




HCl concentrations in smoke gases [ppm]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
Time [min]
Insulation material
Floor covering
Side panel
GRP part
Ceiling over gangways
Ceiling over seats
Seat foam
Lethal > 50 ppm
Intoxication symptoms > 5 ppm
lethal
Intoxication symptoms


HCN concentrations in smoke gases [10 ppm]
300
250
200
150
100
50
0
0
5
10
15
20
Time [min]
Insulation material
Floor covering
Side panel
GRP part
Ceiling over gangways
Ceiling over seats
Seat foam
Lethal > 100 ppm
Intoxication symptoms > 18 ppm
lethal
Intoxication symptoms


HF concentrations in smoke gases [ppm]
10
8
6
4
2
0
0
5
10
15
20
Time [min]
Intoxication symptoms
Insulation material
Floor covering
Side panel
GRP part
Ceiling over gangways
Ceiling over seats
Seat foam
Lethal > 40 ppm
Intoxication symptoms > 10 ppm


$NO_x$ concentrations in smoke gases [ppm]
Time [min]
lethal
Intoxication symptoms
Insulation material
Floor covering
Side panel
GRP part
Ceiling over gangways
Ceiling over seats
Seat foam
Lethal >100 ppm
Intoxication symptoms > 10 ppm


$SO_2$ concentrations in smoke gases [ppm]
Time [min]
lethal
Intoxication symptoms
Insulation material
Floor covering
Side panel
GRP part
Ceiling over gangways
Ceiling over seats
Seat foam
Lethal > 100 ppm
Intoxication symptoms > 4 ppm

# Annex V – General Structure of FDS Input File

```
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&MISC SURF_DEFAULT='MARINITE BOARD', TMPA=20., POROUS_FLOOR=.FALSE. /
&DUMP NFRAMES=1800, DT_HRR=10., DT_DEVC=10., DT_PROF=30. /

&REAC ID          = 'HEPTANE TO CO2'
      FYI         = 'Heptane, C_7 H_16'
      C           = 7.
      H           = 16.
      CO_YIELD    = 0.008 /
      SOOT_YIELD = 0.015 /

&OBST XB= 3.5, 4.5,-1.0, 1.0, 0.0, 0.0, SURF_ID='STEEL FLANGE' /  Fire Pan
...
&SURF ID         = 'STEEL FLANGE'
      COLOR      = 'BLACK'
      MATL_ID    = 'STEEL'
      BACKING    = 'EXPOSED'
      THICKNESS = 0.0063 /
...
&VENT MB='XMIN',SURF_ID='OPEN' /
...
&SLCF PBY=0.0, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
...
&BNDF QUANTITY='GAUGE HEAT FLUX' /
...
&DEVC XYZ=6.04,0.28,3.65, QUANTITY='oxygen', ID='EO2_FDS' /
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[64]