Fire detection & fire alarm systems in heavy vehicles

Final Report

Ola Willstrand, Peter Karlsson, Jonas Brandt

SP Technical Research Institute of Sweden

FFI
Fordonsstrategisk
Forskning och Innovation

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SP Fire Research

SP Report 2016:85

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Abstract

This report summarises the work that has been conducted in a large project about fire detection and fire alarm systems in heavy vehicles. The main goal of the project has been to develop an international test standard for fire detection systems installed in engine compartments of heavy vehicles. For the purpose of defining a test method background information has been compiled regarding fire detection technologies, relevant standards and guidelines, research in the field, durability factors associated with the environment, typical fire scenarios and fire causes. In addition, numerous experiments have been performed in order to provide data to develop the test standard. A separate goal in the project has also been to provide recommendations on fire detection in bus and coach toilet compartments and driver sleeping compartments. Some of the conducted work has been published in three previous SP reports and the work not covered in these is presented in more detail in this report. However, this report summarises all work done in the project.

Key words: fire detection, fire tests, vehicles, test method

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Preface

This work was partly funded by the FFI program of the Swedish Governmental Agency for Innovation Systems, VINNOVA. Also all support from co-partners in the project is gratefully acknowledged.

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Summary

This report presents summaries and conclusions from all work packages in the project “Fire detection & fire alarm systems in heavy vehicles – research and development of international standard and guidelines”. The efforts within WP1, WP2 and WP5 have been published as separate SP Reports, and are presented with a short summary and conclusions in this report. The work within WP3, WP4 and WP6 is summarised more carefully.

The work within WP1 has provided a description of available detection technologies, a summary of relevant standards and guidelines and an overview of up-to-date research in the field of fire detection in vehicles. The efforts of WP2 have provided measurement data and theoretical background of durability factors associated with the environment in engine compartments of heavy vehicles. In WP3 information on fire causes and on how to perform a risk analysis was presented. Such an analysis is required to identify fire risks and to know how to install a fire detection system in a vehicle. Input from WP1, WP2 and WP3 was crucial in the work of defining requirements and scenarios for the fire detection tests included in the test method developed in WP6.

The purpose of WP4 was to test and evaluate relevant fire detection systems to determine characteristics and advantages/disadvantages of the different systems. The tests were the basis for the definition of fire scenarios, test setups, test procedures and test requirements implemented in the new test method.

The work within WP5 has provided recommendations on what type of fire detection system that should be used and how these systems should be installed in bus and coach toilet compartments and driver sleeping compartments. This was the only work package without purpose of providing background information for the development of a new test method for fire detection in engine compartments.

The overall effort of the project and the final work within WP6 has resulted in a new test method; SP Method 5320 “Test method for fire detection systems installed in engine compartments of heavy vehicles”.

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1 Introduction

In June 2013 a project entitled “Fire detection & fire alarm systems in heavy vehicles – research and development of international standard and guidelines” was launched. The project was mainly financed by the Swedish FFI-program (Strategic Vehicle Research and Innovation) which is a partnership between the Swedish Governmental Agency for Innovation Systems, VINNOVA, and the automotive industry. The aim of the project was to develop an international test method for fire detection systems in the engine compartment of buses and other heavy vehicles. All work packages of the project are listed below:

WP1: Survey of fire detection in vehicles
WP2: Factors influencing detector performance in vehicles
WP3: Fire causes and risk analysis for heavy vehicles
WP4: Fire detection systems for engine compartments
WP5: Fire detection in bus and coach toilet compartments and driver sleeping compartments
WP6: Development of international standard

WP1-WP4 were mainly focused on producing background material for the overall goal of defining an international test standard for fire detection systems in engine compartments, WP6. WP5 was not connected to the test standard development, but focused on fire detection in toilet compartments and driver sleeping compartments of buses and coaches, rather than on engine compartments. The purpose was to provide recommendations on the installation of fire detection systems timely with a new UNECE requirement that came into effect 2014 and which states that detectors are mandatory in these compartments.

This report consists of summaries and conclusions from the published SP Reports of WP1, WP2 and WP5. WP3 and WP4 have resulted in internal reports and are summarised in greater detail here. Within WP6 a test method has been developed and published, SP Method 5320, which is briefly presented in this report. The work packages are presented in numerical order starting with WP1.

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2 Survey of fire detection in vehicles (WP1)

The purpose of WP1 was to provide a description of available detection technologies, a summary of relevant standards and guidelines and an overview of up-to-date research in the field of fire detection in vehicles.

The results of WP1 have been published in SP Report 2015:68 “Fire detection & fire alarm systems in heavy duty vehicles : WP1 – Survey of fire detection in vehicles”. The first part of that report gives a general understanding of how a fire can be detected, available technologies and how an alarm system may be structured. The main four fire signatures that are used for detection are gas, smoke, flames and heat. Gas detectors may be constructed to detect incipient gases or gases that are products of the combustion. Smoke detectors mainly react on the soot produced in case of incomplete combustion. Gas and smoke detectors may also be part of a sampling system, meaning that air is sampled and transported to the place where the detector/sensor is positioned. Flame detectors react on the radiation from the flames and may be sensitive to infrared or ultraviolet radiation, or both. At last, heat detectors are sensitive to the heat generated in the combustion process.

The most comprehensive part of the report summarises the standards and guidelines that are most relevant for fire detection in vehicles. No international standard for fire detection in road- or off-road vehicles exists, which was the original rationale for this project. Instead fire detection standards applicable for other areas were examined. There are general approval standards for fire detection, for example EN 54. These are comprehensive and useful standards, however mainly applicable for buildings. In EN 54 it is explicitly stated that it is only valid for detectors used in buildings, but can be used as a guideline for other applications. Regulations and guidelines used in adjacent fields like the rail, aviation and marine industry were reviewed. Also a standard used in the military field was examined. Some national standards used for vehicle application are presented as well, but the content dealing with fire detection in these standards is limited, or focused on risk assessment.

The last part of the report gives an overview of reported and ongoing research in the field: fire detection in vehicles. This overview is very short due to the fact that not much has been published regarding this application. Principally it is SP Fire Research and some organisations in the US that are currently doing research on this, but the published material is very limited.

2.1 Conclusions

The work of WP1 was used as background information when the new test method for fire detection in engine compartments of heavy vehicles was developed in WP6. A test method should be open for all types of detection technologies; both technologies that are used today and those that might be used in the future. The knowledge of different fire detection technologies, provided as an overview in the WP1-report, was important to gain before a new test method could be developed.

The overview of relevant standards and guidelines was used more explicitly in the development work with the new test method. Typical product approval standards, such as EN 54, ISO 7240, FM 3210, UL 268, etc., are comprehensive and cover most issues. However, the tests in these standards are developed for building conditions and do not cover the extreme environments encountered in the engine compartments of heavy vehicles. To be valuable for vehicle application they could be adapted to include these extremes as well as complemented with application specific tests. This is partly done in a

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qualitative way for trains, aircrafts and ships, where the building approval standards are often referred to or used as an example of a product approval standard that could be used as a complement to the application specific requirements. However, the application specific requirements are often very qualitative. For example, for ships it is just stated that a fire detection system shall withstand the environment it is placed in regarding e.g. vibrations, temperature variations and corrosion risks. Some application guidelines, such as the ARGE Guideline for trains, recommends a full-scale application performance test.

There are also some standards, presented in the report, that have some quantitative requirements specific for the vehicle application. Vibrations and shocks are much more severe in a vehicle than in a building, but can also vary a lot between e.g. on-road vehicles and off-road vehicles. Systems for recreational vehicles are, in UL 217, required to withstand a vibration test configuration in 5 days instead of maximum 4 hours, as required for building applications. The test parameters are the same with maximum acceleration of 1.2 g (frequency range 10-35 Hz). STANAG 4317 (off-road) has several vibration tests, but with maximum acceleration of 5 g (frequency range 5-500 Hz) and maximum duration of about 3 hours. FM 5970 (off-road) require maximum acceleration of 10 g (frequency range 10-60 Hz) and 4 hours duration for each axis, complemented with a shock test of 5000 half-sine shocks with maximum acceleration of 10 g.

Temperature variations and humidity tests for recreational vehicles in UL 217 are modified with longer duration times and in EN 14604 they are complemented with a temperature cycle. The maximum and minimum temperatures are around 65°C and -35°C, and are only shifted slightly compared to building applications. In STANAG 4317 temperatures of 85°C and -55°C are used, but during shorter times. However, in these standards the environment in the personal space in vehicles is considered. FM 5970 is more focused on the engine compartment and in this standard more extreme high temperatures are used; 100°C for 180 days (plastics) or 800°C for 15 minutes (metals).

Regarding corrosion tests, all vehicle application standards mentioned above use a salt spray test. Salt is corrosive and commonly applied on winter roads and therefore important to consider for systems used in vehicles.

Input from WP1, as well as from WP2 and from project partners was crucial in the work of defining requirements for the detection system durability tests included in the test method developed within the project.

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3 Factors influencing detector performance in vehicles (WP2)

The purpose of WP2 was to provide measurement data and theoretical background of durability factors associated with the environment in engine compartments of heavy vehicles.

The results of WP2 have been published in SP Report 2015:77 “Fire detection & fire alarm systems in heavy duty vehicles : WP2 – Factors influencing detector performance in vehicles”. The first part of this report presents measurement data from three different types of vehicles operating in different environments. Measured data includes temperatures, both air temperatures and surface temperatures, vibration characteristics, deposition of contaminants, and particle concentrations and size distributions. The measurements were conducted on a city bus driving on different road materials (asphalt and gravel), on wheel-loaders operating on a test track, and on a truck operating in an underground ore mine. For the city bus, measurements were also performed while simulating different harsh conditions, including large amount of exhaust entering the engine compartment and hot surfaces generating water-steam and smoke. A discussion of the large variation of geometry and ventilation conditions for different engine compartments is provided as well.

The second part of the report gives a theoretical understanding of the factors influencing the durability and performance of components in engine compartments of vehicles. The phenomena discussed are corrosion, ageing, temperature variations, vibrations, mechanical shocks, electromagnetic compatibility, and intrusion of water and dust. In relation to each durability factor there is also a summary and discussion of a suitable test method that may be used to verify that the component will withstand the environment.

3.1 Conclusions

The environmental conditions in the engine compartments of heavy vehicles vary greatly, not only from variations in the vehicle design, but from operating in completely different environments, from a regular asphalt road in a city to an underground mine. The work performed in this work package has provided a view of a few common vehicles. Together with information from standards and commonly known facts from combustion engines the following data on environmental conditions could be compiled.

The temperatures of hot surfaces, e.g. turbo charger and exhaust system, in an engine compartment rapidly reach 450°C in the measurements performed in this work package. It is however commonly known that under tougher conditions they may easily reach more than 650°C. The air temperature of an engine compartment varies depending on distances to hot surfaces, ventilation etc. On the cool side of an engine it would rarely be more than 90°C, but at a distance of 20 cm away from the exhaust manifold of a truck, peak temperatures of 190°C were measured and temperatures of above 120°C were maintained for longer periods of time.

The geometry and volume of engine compartments generally vary from 10 m^3 to 1 m^3, excluding very large heavy duty mobile equipment. Some compartments have no or few components in some areas, while other compartments are completely cluttered from floor to ceiling. The area around the engine is often similarly cluttered with components situated quite tightly together, but the rest of the compartment could be either almost empty or fitted with extra equipment.

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Ventilation and airflow is another subject which differs from vehicle to vehicle. Some compartments are almost completely sealed with no airflow, while others have high air exchange rates or are open to the surroundings.

Vehicles are exposed to vibrations and mechanical shocks from just driving and occasionally hitting a road bump. The performed vibration measurements showed peak accelerations of as much as 8.5 g and almost constantly showed accelerations between 0.2-1 g (removing the background gravitational acceleration).

An engine compartment of a vehicle has an environment which is often very corrosive with varying temperatures and humidity, and road salt during the winter months. Hence the components installed in an engine compartment must have high corrosion resistance.

Particle and dirt contamination varies mostly due to external conditions and where the vehicle operates, but also the grade of enclosure and ventilation rates will have a big impact on the amount of particles getting into the engine compartment.

It is of high importance that components installed in the engine compartments of heavy vehicles manage the environmental conditions discussed above. Suitable standards and test methods are discussed in the WP2-report, which together with input from measurements, from project partners and from WP1 laid the foundation for the durability tests and requirements included in the development of the new test method.

Some requirements, e.g. corrosion resistance, were implemented with the same requirements for all types of vehicles, while other environmental conditions, such as vibration requirements, needed different levels for on-road vehicles and off-road vehicles. Exposure to particles and different ventilation conditions in appropriate geometries were included in the detector performance tests (fire tests).

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4 Fire causes and risk analysis for heavy vehicles (WP3)

The purpose of WP3 was to provide information on fire causes and on how to perform a risk analysis. An analysis is required to identify fire risks and to know how to install a fire detection system in a vehicle.

The work included a theoretical study of what conditions are needed to ignite and maintain a fire, and which fire causes and ignition sources that can be expected in a vehicle, primarily in the engine compartment. Fire investigators were consulted regarding what fire causes they have experienced and several statistical studies were reviewed.

Within the work package a bachelor's thesis regarding bus fires in Sweden between 2005-2013 was written in order to provide statistics on e.g. number of fires, fire origin, fire extent and firefighting actions.

From the information gathered in the work package, guidelines for what to include in a risk analysis was produced.

4.1 Fire Causes

For vehicles, like everything else, the same general fire conditions apply. To start and maintain a fire the principles of the fire triangle need to be followed, see Figure 1. A fire needs heat, fuel, and oxygen. Without any of the three the fire will be extinguished.

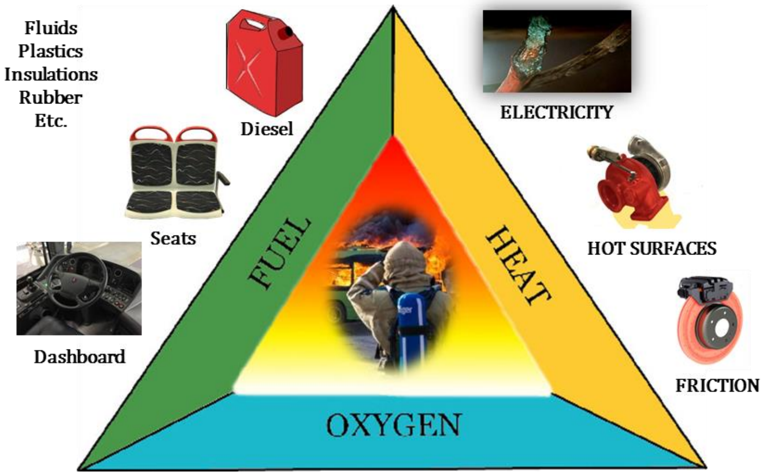

Figure 1. The fire triangle with heat, oxygen, and fuel, each representing one side of the triangle. If one side is lost the fire triangle is broken and fire will not occur.

In a vehicle the oxygen supply will normally be sufficient to maintain a fire except for fires starting in well enclosed spaces, e.g. a fire starting inside the driver cabin may self-extinguish due to lack of oxygen.

Vehicles carry a lot of fuel. Seats, interiors, tyres, plastic exteriors, plastic hoses and tubes, cable insulation, batteries as well as the actual fuel used to propel the vehicle, hydraulic oil, lubricants, motor oil, cooling liquid, de-icing agents etc. are all possible fuel sources. Cargo also constitutes a fuel source and so does accumulated combustibles like dirt, wood chips and garbage.

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Instead of heat the term ignition source is used, which is any heat source in the vehicle which can produce enough heat to start a fire. Ignition sources are parts or components which produce heat either at normal operation or when malfunctioning. Among these sources are parts of the combustion engine (the exhaust system including e.g. exhaust manifold and turbocharger), parking heaters, friction heat from moving parts (e.g. brakes) and electronic malfunction (e.g. short circuits from insulation faults).

For a fire to start one would basically need an ignition source and a fuel source to come into contact with each other. A properly functioning vehicle will keep these two separated, but if the separation fails it may cause a fire. Failures like these can be e.g. fuel leakages which may ignite when the liquid fuel gets heated by the turbocharger, lost integrity of the exhaust system causing hot air to come in contact with plastics, and cable insulations worn so thin that the cable may short circuit to a grounded part. These three mentioned hazards are all, except from worn cable insulation which may occur anywhere, located in the engine compartment. Engine compartments are the most common fire origin area. However, fire hazards are present in practically all areas of a vehicle.

4.1.1 Hot Surface Ignition

A master thesis [1] study on hot surface ignition temperatures for diesel and alternative fuels was conducted as a part of WP3. The study set out to determine probability of ignition at different surface temperatures and the influence of droplet size. Regarding droplet size it was found that larger droplets of heptane will ignite easier than smaller ones, at least within the tested range presented in Figure 2. The same observations were made from tests using HVO (Hydrogenerated vegetable oils).

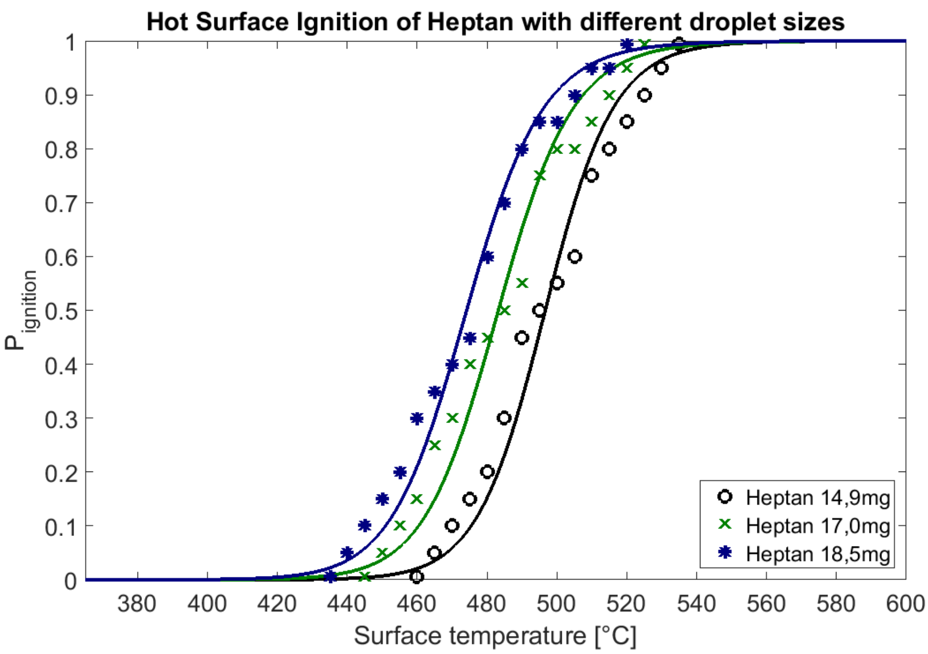

Figure 2. Hot surface ignition with different droplet sizes with 20 trials (probability of ignition presented) at each specific surface temperature. [1]

Hot surface ignition temperatures and the probability of ignition for different fuels were tested and the results are presented in Figure 3. It could be concluded that the alternative fuels ignite at lower surface temperatures. The HVO-curves in Figure 3 visualise what is likely to be the Leidenfrost effect. It is believed that the other curves would also start showing a likelihood of ignition that decreases with increasing temperature at some point,

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but no tests were made in that temperature region. The Leidenfrost effect is in short a phenomenon which occurs when a liquid comes in contact with a surface of much higher temperature than the liquid's boiling point. A thin and isolating vapour layer is then created between the hot surface and the liquid droplet, which is prevented from rapid vaporization and consequently it is also prevented from igniting.

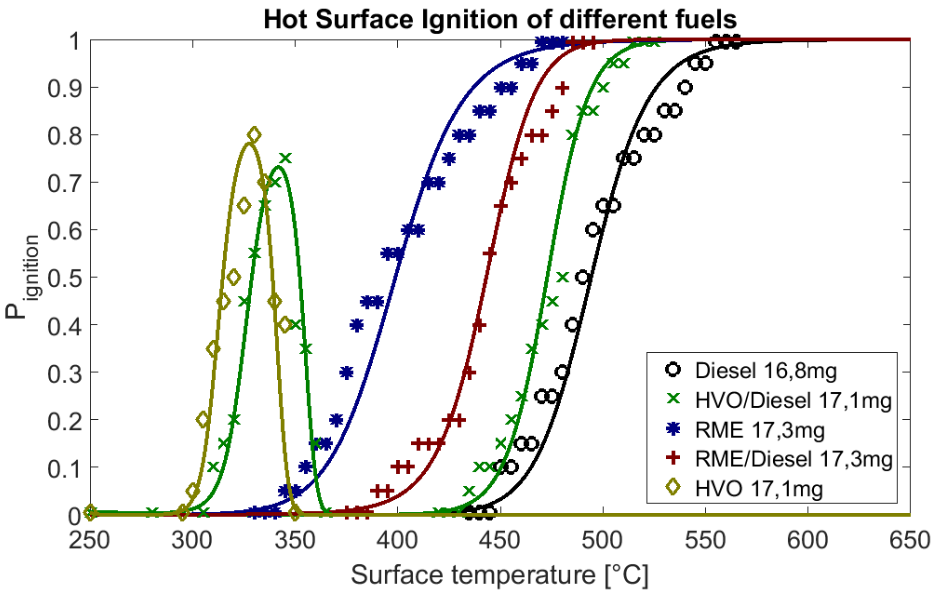

Figure 3. Hot surface ignition of different fuels with the same droplet size. HVO/Diesel and RME/Diesel means that these fuels are mixed 50/50. [1]

4.1.2 Statistics – Review of bus fires in Sweden

Within the project a bachelor's thesis [2] and, shortly after, a SP Report [3] was written in order to provide statistics on bus fires in Sweden.

The survey was limited to only examine bus and coach fires in commercial traffic in Sweden. The data is entirely based on the MSB´s database on bus fires between years 2005 – 2013 and does not take into consideration the number of potential unreported cases.

In 2006 a mapping of bus fires in Sweden was made by SP, covering the period between 1996 and 2004. The thesis report includes a brief review of the previous survey in order to obtain an overall picture.

The following conclusions can be drawn from the results obtained regarding bus incidents frequency, fire origin area, fires extent and extinguishing efforts:

- Average number of the reported bus incidents per year related to fire between 2005 and 2013 is 104. The lowest number of incidents is registered in 2012 and 2013, but studying the whole period no definitive conclusion regarding a downward trend can be made. In order to reach such a conclusion, the number of incidents needs to remain at the 2013 level, or even continue to decline in the following years. Furthermore, it is reasonable to assume that there are a number of incidents that do not get reported to the FRS (Fire Rescue Service).

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- Buses involved in incidents related to fire between 2005 and 2013 correspond to a yearly average of 0.76% of the total bus fleet in commercial traffic. This figure presents a general description of the reality. However, it does not reveal details about the vehicles involved in the accident. To address this problem, the proposal is to link the incident report to the Transportation Board's database of vehicle information. In this way, all the relevant information on the vehicle involved in the incident, such as the manufacturer, model, age, number of days in operation, distance travelled, fuel type, etc., could be obtained and registered in the incident report simply by recording the license plate number of the vehicle. This data could then be used in a more specific way to draw conclusions regarding vehicles involved.

- Engine compartments are with 64% of the cases by far the most common origin area for fire incidents on buses, and wheel well the second with 20% of the cases. To more specifically identify the cause of fires requires processing of the data from other sources; such as incident reports from the bus companies, bus manufacturers and insurance companies.

- Total loss of the vehicle was the result in 7% of all recorded incidents between 2005 and 2013. In 49 % of registered total losses the fires originated in the engine compartment, in the remaining 51% of cases the origin area was unknown. The number of total losses varies during the studied period and there is no indication if the trend is moving downward or upward.

- FRS conducted action on average in 55% of call outs. The number of incidents which have required extinguishing effort from FRS has been on a slightly downward trend since 2006.

- Bus drivers have a significant role in the initial extinguishing effort. Bus driver (or staff) extinguished the fire in 26 % of the occurred fire incidents between 2005 and 2013. Nevertheless, improvements can be made in bus drivers' education and training in terms of more solid guidelines and skill requirements regarding fire safety issues. Such an improvement could potentially lead to more bus fires being restricted or eliminated prior to FRS arrival.

4.1.3 Statistics - Compilation of several studies

Statistics on fire causes are compiled from different studies performed in the U.S, Australia, New Zealand, Finland and Sweden. The results are presented in bar graphs.

In Figure 4 statistics on fire causes from bus fires in Finland 2010-2011 is presented. The most common cause is from electrical failure, closely followed by friction heat from brakes or bearings.

In Australia the most common stated fire cause in buses between 2009 and 2013 was mechanical failures in engine compartments followed by electrical failures in the engine compartment, see Figure 5.

Between 1999 and 2003 bus and school bus fires in the U.S. were mainly caused by mechanical failures. The second most common cause was electrical failures. The first item most often ignited was electrical wire insulation followed by flammable liquids, see Figure 6. Statistics from 120 bus fire investigations between 2002 and 2006 in the U.S. illustrates what or who caused the failure which lead to the fire. The most common cause was a random failure while a deficient design from the manufacturer and lack of skill during maintenance was found to be second and third most common, see Figure 7.

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Another study from the U.S. concerning motorcoach fires between 1995-2008 identified brakes and tyres as the most common ignition points with turbochargers being third most common. Failed wheel or hub bearings was fourth most common and electrical failures in the engine area was fifth, see Figure 8.

Figure 9 provides information on non-intentional automobile fires in the U.S. between 2006-2010 and shows in which area the fire started and also connects the origin to deaths and injuries in the different accidents.

In Swedish underground mines electrical failures are the most common cause of fire while mechanical failures also hold a fairly large proportion of the fire causes between 1988 and 2010, see Figure 10.

A study on vehicle fires in parking buildings from 1995-2003 in New Zealand, see Figure 11, show that disregarding deliberately lit fires or exterior fire causes from e.g. hot works the electrical failures account for the majority of the fires while mechanical failures including leaks are also quite commonly occurring. Note that while the fires took place in parking buildings they have not exclusively started in parked, powered down vehicles.

Bus fires in Finland

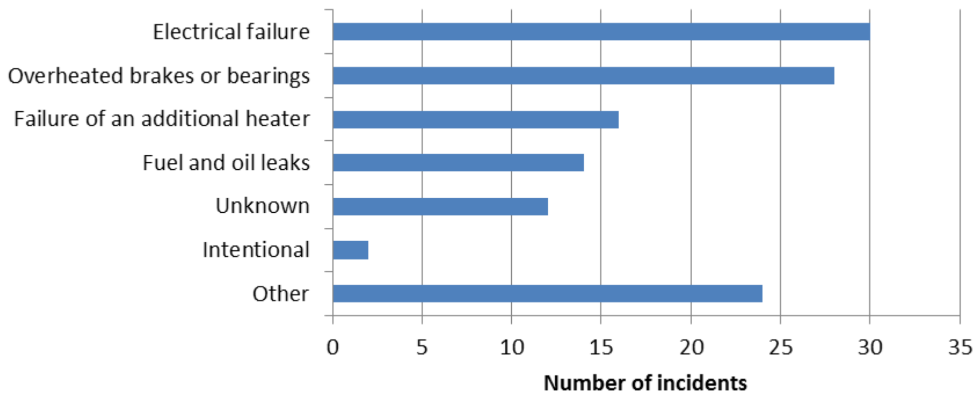

Figure 4. Bus fires in 2010-2011 in Finland. Source: E. Kokki, Bus Fires in 2010-2011 in Finland, FIVE 2012, Chicago.

Bus fires in Australia

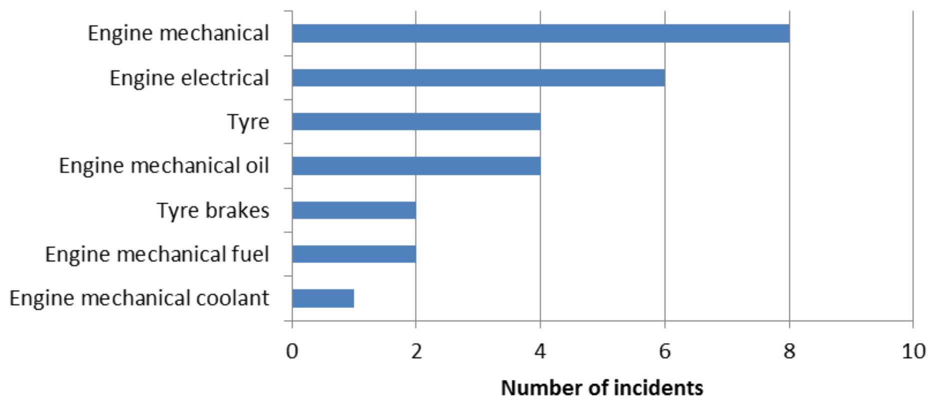

Figure 5. Reviewed Australian bus fire incidents between 2009 and 2013. Approximately 85 bus fire incidents were reviewed, but detailed information on fire origin was only found on 27 incidents. Source: Bus Industry Confederation Inc., Fire Mitigation Advisory, Australia, 2014.

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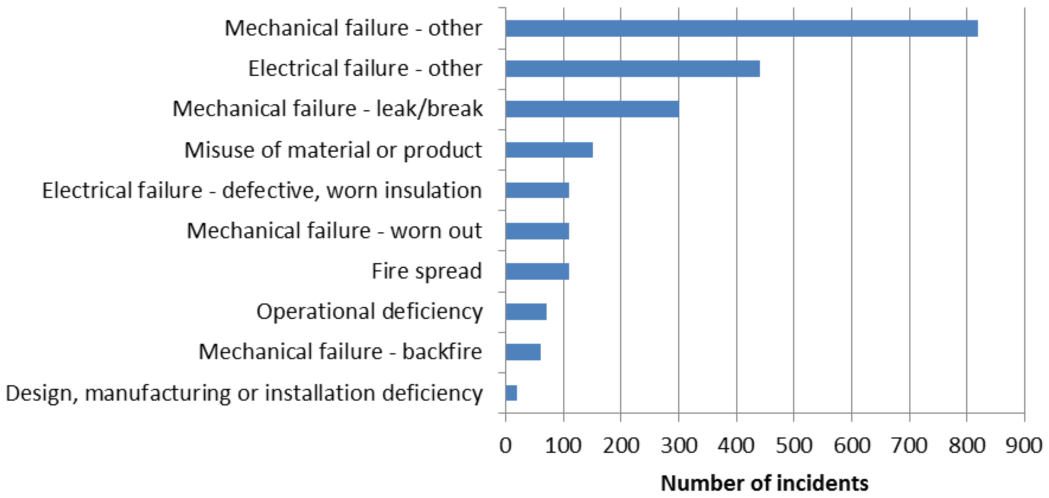
Bus fires in the US



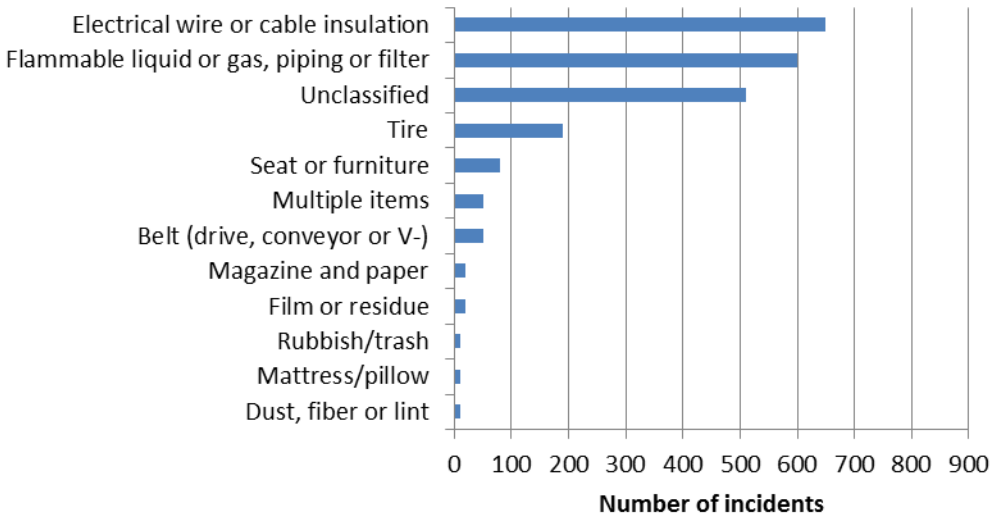


Figure 6. U.S. bus and school bus fires, annual averages between 1999-2003. Upper diagram: Fire causes. Lower diagram: Item first ignited. Source: M. Ahrens, Vehicle fires involving buses and school buses, NFPA, US, 2006.

Bus fire responsibilities in the US

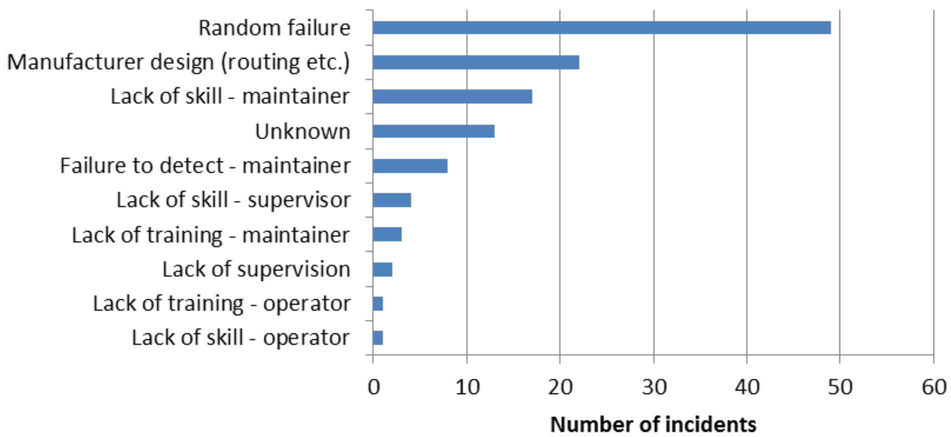


Figure 7. 120 bus fire investigations in US between 2002-2006. Diagram shows who was held responsible. 89 of 120 fires are related to electrical and high pressure fluid line failures. Source: Public Transportation Safety Board, Bus fire analysis – Investigations 2002 through 2006, US, 2008.

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Motorcoach fires in the US

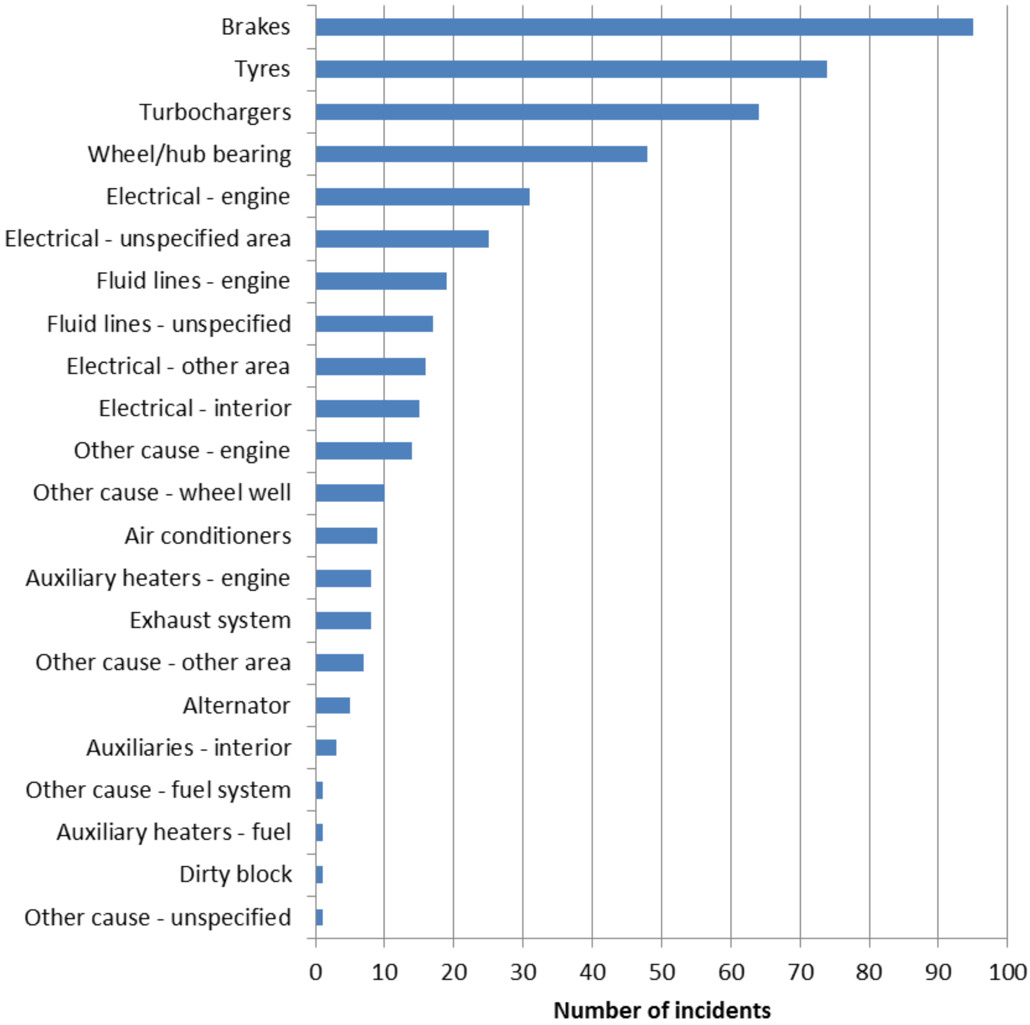
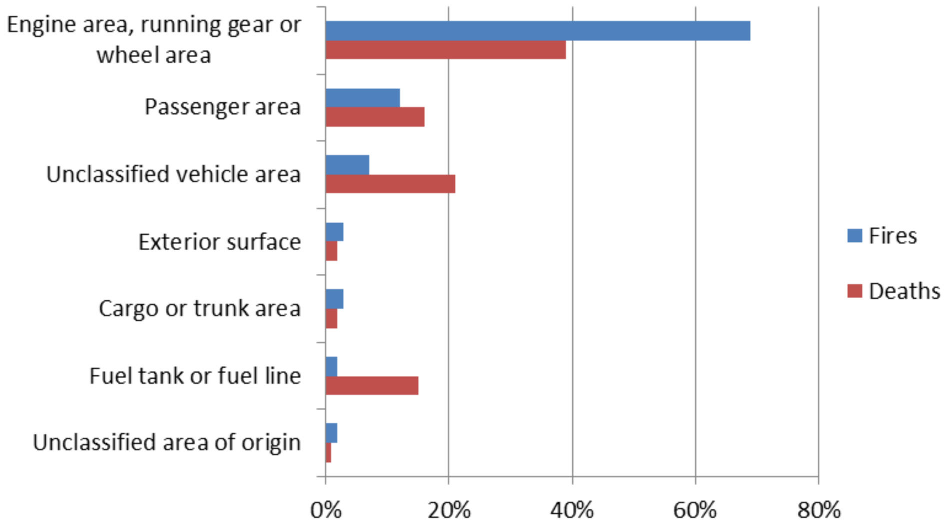


Figure 8. Reported ignition points of motorcoach fires in the US between 1995-2008. Source: N. R. Meltzer, G. Ayres and M. Truong, Motorcoach Fire Safety Analysis: The Causes, Frequency, and Severity of Motorcoach Fires in the United States, FIVE 2012, Chicago.

Automobile fires in the US



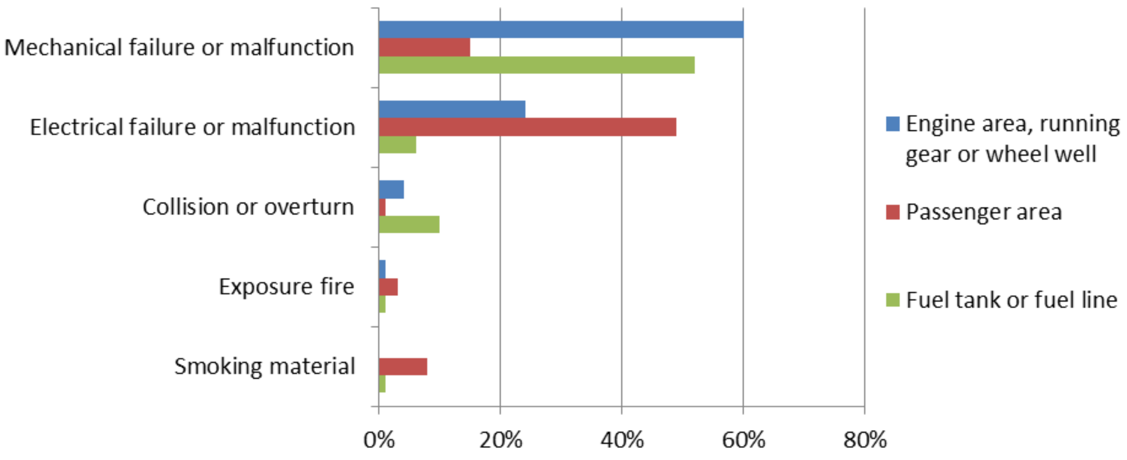


Figure 9. Non-intentional automobile fires in the US between 2006-2010. Statistics are based on about 450 000 reported automobile fire incidents, including cars, buses, trucks, etc. Source: M. Ahrens, Automobile Fires in the U.S.: 2006-2010 Estimates, FIVE 2012, Chicago.

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Vehicle fires in Swedish underground mines

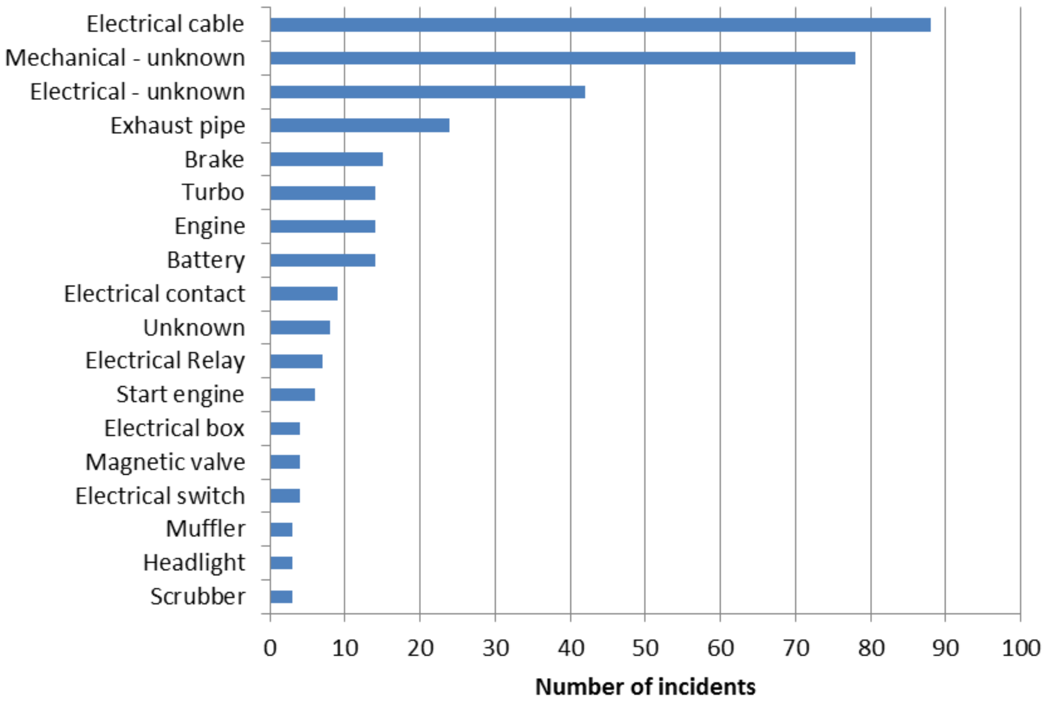

Figure 10. Vehicle fires in underground mines 1988-2010. Source: R. Hansen, Investigation on fire causes and fire behaviour – Vehicle fires in underground mines in Sweden 1988-2010, Mälardalen University, Sweden, 2013.

Vehicle parking fires in New Zealand

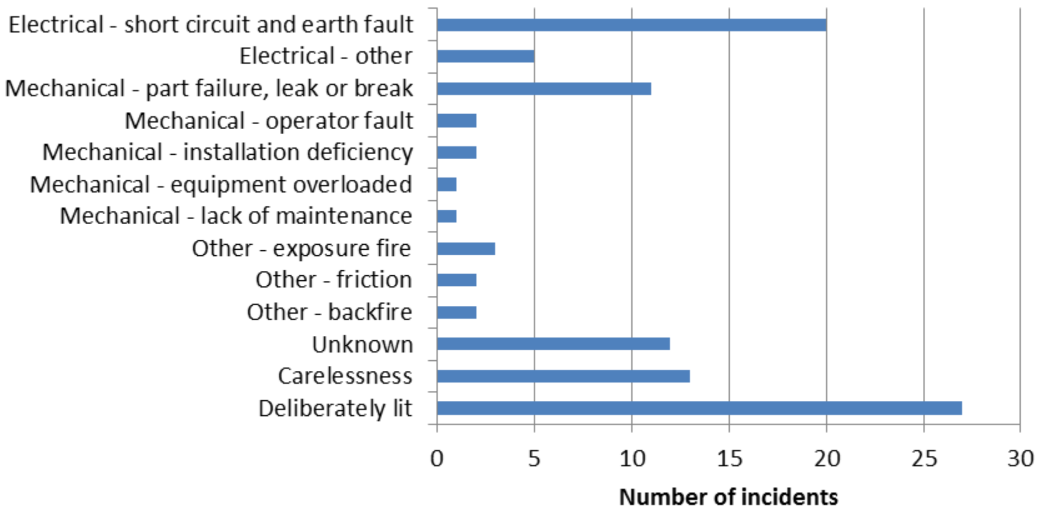

Figure 11. Vehicle fires in New Zealand parking buildings from 1995 to 2003. Source: Y. Li, Assessment of Vehicle Fires in New Zealand Parking Buildings, University of Canterbury, New Zealand, 2004.

4.2 Risk analysis guidelines

The hazards identified in the previous sections are important input to what to focus on in a risk analysis. The aim of the risk analysis procedure is to identify the locations of the fire hazards in an engine compartment, determine the possible consequences from an incident at those locations and decide how to install a fire detection system in order to detect the fire. Depending on the environment of the hazard location and the nature of the hazard the fire may stay limited in size, meaning less need of early detection, or grow fast, meaning great need of early detection.

In this section a general procedure is presented followed by a few common hazards and hazardous designs which should be controlled in a risk analysis. The work has also been implemented in a new SP Method for risk management, “SP Method 5289 – Fire Risk Management Procedure for Vehicles”.

The most important part is the hazard identification, but both the risk estimation and the risk evaluation parts may provide useful information.

4.2.1 Hazard identification

The fire triangle was introduced in section 4.1 and it could basically be said that where there is a possible interaction between fuel, ignition sources and oxygen there is a fire hazard. The hazard identification process aims to first and foremost answer where this could happen, when it could happen, how it could happen, but also why it can happen.

Identified fire hazards on old vehicles that have been used for some time generally include hazards related to wear and tear. To determine fire causes are crucial for the identification of similar fire hazards, but can be a complex work since there are often several indirect or underlying causes beyond the primary cause. For instance, a primary cause of fire could be a hot surface of the exhaust system igniting some combustibles. An underlying cause could then be a fuel hose rupture, which in turn could be caused by abrasion due to a loose attachment. This, in turn, could possibly be caused by faults during the fitting of the attachment.

Determined fire causes may as well be used to identify the most important fire hazards by examining the surrounding materials and determining fire spread and development following ignition. It is important to not only consider where the first ignition could take place, but also where the fire would start growing and how to design the fire protection. Small fires are more difficult to detect than large ones and at the location of the ignition the fire may stay undetectable for some detection systems even though the fire spreads to a different location. Ventilation may e.g. blow glowing embers from the place of ignition, e.g. the exhaust manifold, to a plastic component downstream and there it may ignite the plastic materials. The environmental conditions in an engine compartment have huge effects on both fire development and fire detection performance, therefore it is important to consider e.g. the airflow around the identified hazards in order to know where the fire detector should be placed for optimal performance.

Statistics and historical events should always be taken into consideration while performing hazard identification to decide which areas are most in need of detection coverage and rapid detection.

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Example of a hazard and its complexity

During a fire investigation in 2014 the fire cause was found to be a burning ember blown from a pocket at the muffler forward to the combustible materials above the front left tyre, i.e. the mudguard. The pocket where the wood chips were accumulating was an identified hazard and well protected with both a linear heat detector and five nozzles from the suppression system directed towards the muffler and the pocket, see Figure 12.

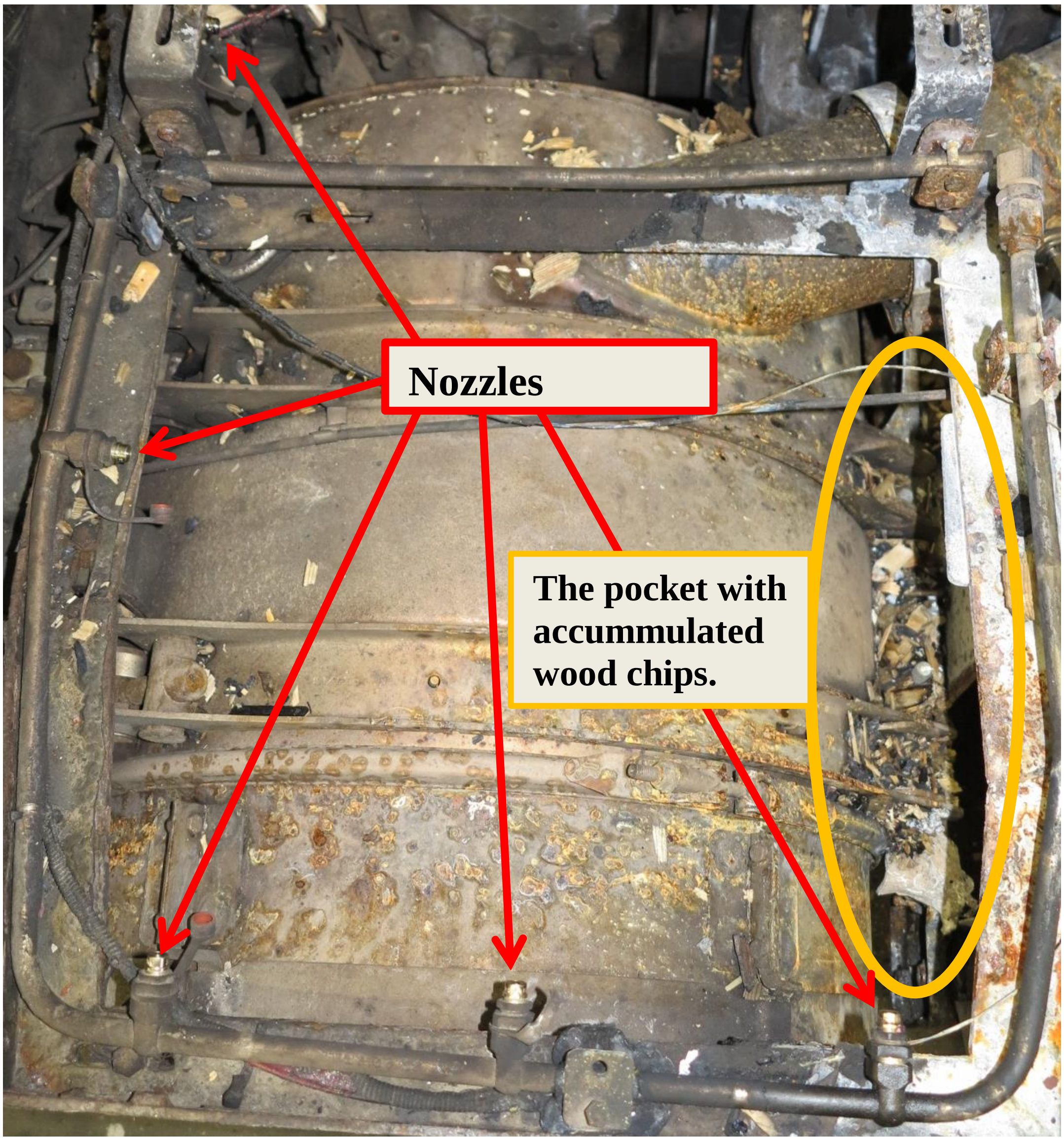

Figure 12 The muffler with surface temperatures of several hundred degrees Celsius is obviously an identified hazard and well protected.

While a fire is likely to ignite here and the accumulation of combustible wood chips is a likely fire cause, the fire is not likely to grow very large here. It has to spread somewhere else to grow and according to this fire investigation that is what happened, but not in the sense that it grew here and spread due to the heat produced and by flames. It spread because one or two of the glowing embers from the pocket in front of the muffler followed the wind to land further in contact with the mudguard in front of the muffler and that is where the fire started growing, see Figure 13. This area was more or less unprotected; the fire detection system did not cover that area and the fire suppression had no chance of extinguishing a fire in that area.

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This example shows the need of not only identifying the locations where a fire is likely to ignite, but also where it may spread to before it is detectable. It is important to take both air movements and locations of combustible materials nearby an ignition source in consideration when deciding how to install both a detection system and a suppression system.

Figure 13 The muffler from Figure 12 is situated in the left in this picture whereas the fire started growing above the tyre, where the mudguard has been consumed by the fire.

4.2.2 Risk estimation

Following the hazard identification, risks should be quantified by a risk estimation method. There are several different methods that could be used, and most of them are based on estimations of the likelihood and consequence of the identified hazardous events. The objective is to quantify the risks in order for them to be sorted with respect to priority and actions needed.

A method often used in the vehicle industry is Failure Mode and Effects Analysis (FMEA). This method can also be applied for quantification of the vehicle fire risks. The identified hazards (failure modes) are given risk priority numbers based on quantifications of probability of occurrence, severity, and probability of detection failure.[1] Each of the quantifications is made on a relative scale where a higher rating contributes to a higher estimated risk priority number.

Fire severity can be quantified by estimating the potential consequences for the vehicle, the driver and passengers, as well as to the surrounding environment. For example, the location and type of fire could affect the fire growth rate, the extent of the fire, evacuation time for the driver and passengers, and also the possibility to extinguish the fire.

The probability of occurrence can be estimated based on fire statistics, but also with consideration to operational conditions for the specific vehicle. Operational conditions include, but are not limited to:

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[1] Note that detection failure here means failure to notice e.g. an abrasion in the isolation of a battery cable during an inspection. It has nothing to do with fire detection.

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- Maintenance practices
- Operating environment
- Operator experience and human errors
- Wear and tear and life cycle of components

Finally, the probability of detection failure can be estimated with consideration to the means for detection available. For fire risk estimation with use of FMEA, detection do not in this case include fire detection but only detection of the hazard that might result in a fire. Means for detection can e.g. include maintenance and inspection routines, driver routines and training, tyre pressure monitoring system, brake system high temperature warning, etc. It should be noted that the rating should only be lowered if an early detection would prevent the start of a fire.

4.2.3 Risk evaluation

When the fire risks are quantified as described above, they should be sorted to provide an overview of the risk image. The risk evaluation aims to provide this overview and to separate the risks which need to be specifically addressed from risks that are just subjects to a basic level fire detection need.

The matrix in Figure 14 below could be used for guidance.

RISK ASSESSMENT MATRIX				
Severity / *Probability*	Catastrophic	Critical	Marginal	Negligible
Frequent	High	High	Serious	Medium
Probable	High	High	Serious	Medium
Occasional	High	Serious	Medium	Low
Remote	Serious	Medium	Medium	Low
Improbable	Medium	Medium	Medium	Low

Figure 14. Fire risk assessment matrix.

Actions corresponding to the different risk ratings could be:

- High/Serious – Rapid fire detection needed. System installation should consider how to detect a fire immediately after or before ignition.
- Medium – Relatively rapid fire detection needed. Fire should be detected before it spreads to nearby areas.
- Low – Unlikely to cause rapid fire growth or rapid spread of fire. Sufficiently protected by a basic level of fire detection.

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4.3 Conclusions

A fire needs heat, fuel and oxygen. In an engine compartment oxygen is normally sufficient. This means that what is critical to avoid fires is to keep fuel and heat separated.

The heat sources are parts of the exhaust system (from manifold and turbocharger and further to the exhaust system), friction from moving parts (e.g. faulty brakes or other mechanical failures), electronic failures (e.g. component failures, isolation faults). Sparks may also be generated from e.g. alternators. Fuels sources are all combustible materials (e.g. insulation materials, plastic parts, tubes, hoses, filters) and the flammable liquids (oils, diesel).

To avoid fires fuel lines should be kept at one side of the engine and the exhaust system on the other. Solid combustibles like plastic components should be kept at a safe distance from hot surfaces. However, separation between heat sources and combustibles is not always possible; cables have plastic isolation and brakes are of course close to the tyres. The most common fire causes are electrical cables, mechanical failures, tyre or brake failures, liquid fuel leaks on hot surfaces and electrical component failures.

In Sweden between 2005-2013 a yearly average of 0.76% of the total commercial bus fleet were involved in fire related incidents. The most common area of origin was the engine compartments (64%) and wheel wells (20%). Total losses occurred in 7% of the recorded events and in 49% of the total losses the fire originated from the engine compartments. The other 51% originated from “unknown” locations. In 26% of the fire incidents the bus driver (or staff) extinguished the fires.

When it comes to risk analysis it was found important to not only concentrate on fire causes, ignition sources and their locations, but to also consider the following fire development, fire growth and spread. At locations were the fire likely will grow slowly the need for early detection might be less, but at locations were the fire will grow rapidly or where the risk of fire spread to critical components or to driver or passenger compartments is big there is need for faster detection. Where the fire starts growing is deemed to be just as important for detection systems as where it starts. It is important to cover all aspects of fire causes when performing a risk analysis; risk designs, historical fire causes, maintenance practices, operating environments and wear and tear and life cycle of components.

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5 Fire detection systems for engine compartments (WP4)

The purpose of WP4 was to test and evaluate relevant fire detection systems to determine characteristics and advantages/disadvantages of the different systems. The tests were the basis for defining of fire scenarios, test setups, test procedures and test requirements implemented in the new test method developed in WP6.

The WP4-report included two parts: a technical description of fire detection technologies commonly used in engine compartments or technologies that are relevant but not yet implemented, and an overview of test results from tests performed to evaluate different fire detection technologies.

5.1 Fire detection technologies

This chapter presents fire detection technologies that are either commonly used in engine compartments or technologies that are relevant but not yet implemented or used frequently in engine compartments of heavy vehicles. Provided is a technical description and an understanding of how the different systems work.

5.1.1 Heat detection systems

Heat detection is today by far the most common way to detect fires in the engine compartment of heavy vehicles. Both point heat detectors as well as linear heat detectors are common and some technologies that are used are described below.

Point heat detectors

Thermocouples are one technology that can be used to monitor the temperature. They consist of two conductors of different material joined together at the point where the temperature is to be measured. The voltage difference between the conductors in the other end, positioned in a known reference temperature, will be proportional to the temperature in the joint. This is based on the Seebeck effect which states that the gradient of voltage in a conductor with no internal current flow is directly proportional to the gradient in temperature [4]. The measured temperature can then be interpreted in different ways to activate an alarm either on rate-of-rise of temperature or at a fixed temperature.

Also other technologies can be used to measure the temperature in a point. Thermometers include several physical temperature phenomena that can be converted into a numerical value e.g. thermal expansion of solids and liquids, pressure change of a gas, change of resistance in a sensor (thermistor and resistance temperature detector, RTD), or infrared radiation (IR thermometer and thermal imaging camera) [4]. Some of these physical phenomena can also be used in a direct way without conversion to a numerical value and monitoring of the temperature. For example, activation due to that a glass bulb breaks as a result of the thermal expansion of the liquid inside the bulb is common in sprinklers but is also used in detection systems. A similar technology to the breaking glass bulb is the fusible link heat detector. Instead of a glass bulb that breaks at a fixed temperature the fusible link heat detector make use of the melting point of an alloy. The melting of the element breaks an electrical circuit causing the activation of an alarm or a sprinkler. [5]

Bimetal heat detectors make use of the thermal expansion of solids [4]. Two different metals are joined together, and due to different coefficients of thermal expansion the temperature change can be converted into mechanical displacement, see Figure 15. The mechanical displacement can in turn activate an alarm.

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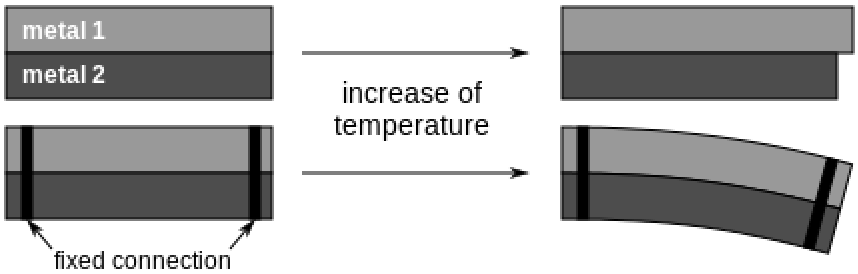

Figure 15. The principal of non-heated (left) and heated (right) bimetal. [6]

Linear heat detectors

Linear heat detectors use a hose or cable to detect heat along the entire length of the sensor. The different technologies are in many cases similar to what is used for point heat detectors. For example, change of resistance in a conductor or pressure change of a gas in a hose is widely used. Such detectors are often called “averaging linear heat detectors”, which means that the detector makes no difference between a small temperature increase over the entire length and a large increase at one point as long as the change of resistance/pressure over the whole length is the same. In addition, the point of a large temperature increase cannot be localized. However, these detectors have the ability to monitor the temperature continuously and have the possibility to activate an alarm on either rate-of-rise or at a fixed temperature.

Two of the most common linear heat detectors used in engine compartments of heavy vehicles are based on polymer degradation and melting. In one of the two technologies the sensor cable consists of two conductors, each insulated with a heat sensitive polymer. The insulated conductors are protected by an outer jacket. At the activation temperature the heat sensitive polymer melts and the conductors will short circuit, initiating an alarm.

The other common technology uses a pressurised hose which bursts at a specific temperature. The main reason for the burst is degradation of the polymer, however, the pressure in the hose will affect the temperature needed for the hose to break. When the hose bursts the pressure in the system falls which activates an alarm. The system can contain gas or liquid. Some manufacturers have opted to use liquid from experience that liquid systems have less problems with leakages and unwanted pressure falls. This type of activation can also be used directly on the suppression system, such that the suppression agent is released when the hose bursts.

A technology that is used in e.g. the aviation industry, but to our knowledge has not been used in engine compartments of heavy vehicles, is optical fibre heat detectors. A temperature rise in one part of the optical fibre will change the refraction and scatter properties. Change in refraction will be registered by a sensor in one end of the optical fibre due to changes of the back-scattered light in the fibre. The position where the temperature increase of the optical fibre occurs can be determined by measuring the time of a light pulse to go back and forth to the point of refraction change (a portion of the light pulse will be back-scattered at this point). This type of systems can initiate an alarm either on rate-of-rise conditions or fixed temperature conditions. [7, 8]

5.1.2 Flame detection systems

In engine compartments of heavy duty vehicles flame detectors are sometimes used as a complement to heat detectors, but could also be used alone if they are designed for that purpose. The reason to complement the fire detection system with flame detectors is to get a very fast response in case of fast developing flaming fires, e.g. ignition of a ruptured fuel line.

Flame detectors react on the electromagnetic radiation from flames, which include the infrared (IR) spectrum, visual light, and the ultraviolet (UV) spectrum. Most flame detectors are constructed to detect radiation at several different narrow or wide wavelength regions to avoid false alarms. It can be a combination of IR and UV regions or just different regions in the IR spectrum. For example, in fires there is a lot of radiation at wavelengths around 4.3 µm due to molecular vibration of carbon dioxide, which is a fire product. The relationship between radiation at this wavelength and other wavelengths is then often different for fires compared to other hot objects and other potential sources for false alarms. [9, 10]

False alarms may also be avoided by looking at the fluctuation of radiation. The fluctuation frequency at a specific wavelength could be very different for a flame compared to other radiation sources.

A third way to avoid false alarms is to let the detector compensate for small and slow changes in radiation. For example, increased heat radiation from the turbocharger will be neglected, but a large and sudden flame will generate an alarm. The drawback of these detectors is that they will be insensitive to slow-growing fires.

Flame detectors can either use thermal sensors or photonic sensors. A common thermal sensor is the pyroelectric sensor, which generates a temporary voltage when heated or cooled. This type of sensor can be used to detect fluctuations or large changes in the IR radiation spectra. To measure constant levels of radiation and radiation in the UV region semiconductor photodiodes are often used. These sensors convert incident photons into charge carriers. Photonic sensors are often associated with higher sensitivity and faster response compared to thermal sensors, but to a higher cost and in some cases less robustness. [11]

Since a flame detector must “see” the flames it is important that the detector lens is not obscured by dirt, ice, and oil. Different wavelength regions will be affected more or less by the different contamination products [9]. Some detectors also have the ability of lens supervision and will generate a warning signal if the lens is obscured more than acceptable.

5.1.3 Smoke/gas detection systems

Smoke and gas fire detection has not been considered for engine compartments of heavy vehicles in the past due to the harsh environmental conditions and high risk of false alarms. The Vulcan project [12] has modified this previous view on smoke detection systems and there are now other market players showing interest in this. The benefit of smoke and gas detection is very early warning in case of smouldering fires and slow-growing fires, characteristic to electrical fires.

Smoke and gas detection systems can either be of point type or aspirating type. Aspirating detectors use a sampling pipe network to draw air from one or several points through the pipe network to the detector unit. The benefits of using aspirating systems are that the detector can be placed outside the harsh environment of the engine compartment and that one sensor can cover more than one point in space. Furthermore, it is easier to apply filters, which clean the air from particles not characteristic for fire smoke. [13]

For household applications both ionisation smoke detectors and photoelectric smoke detectors are used, but detector suppliers to the vehicle industry and aspirating smoke

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detector system suppliers use almost exclusively the photoelectric principle. These detectors have a light source and a photo detector in the smoke chamber to either register light scattered by the smoke particles or light obscured by the smoke particles.

Filters, drift compensation, dual wavelengths and photodiodes at multiple scattering angles are examples of methods used to avoid false alarms in smoke detectors. Several wavelengths and scattering angles are used to determine particle size and drift compensation is used to compensate for dust and dirt or aging of the optical components. Most detectors have a warning system to alert the user if the detector is unable to compensate anymore or if the filter is clogged.

There are several different types of gas detectors that are used for various applications [10]. One interesting technology that is used in other harsh environments, e.g. in tunnels and coal mines, is called electronic nose. It uses several semiconductor sensors to “smell” different gases. The relative concentrations between the different gases give patterns such that the detector recognises if the “smell” is from combustible gases, an actual fire or from a false alarm source. [14]

5.2 Detector performance

Tests were performed in WP4 to evaluate different fire detection technologies and to develop the new test method (WP6). Between the tests with different suppliers and different fire detection systems the test configuration was changed to implement new ideas and experience from earlier tests. This is a natural part of developing a test method. It also means that a precise comparison between different types of fire detectors cannot be presented. However, in the future the completed test method will be an accurate and repeatable basis for comparative tests between different fire detection systems applicable for engine compartments of heavy vehicles.

Presented below are an overview of test setups and a summary of test results for different types of detection technologies. Heat, flame and smoke detectors were tested, but not gas detectors.

5.2.1 Heat detectors

Several different heat detectors were tested in a heat tunnel to determine activation temperature and response times. The heat tunnel used can be seen in Figure 16. The airflow velocity could be altered up to approximately 2.5 m/s. Most tests were conducted in 1.5 m/s with a constant air flow, but in some tests the mass flow was held constant which means that the velocity increased with increased temperature. However, no distinctive differences were obtained for air flow velocities varying from 1.5-2.5 m/s. Detectors were mounted in different ways (the tunnel was not adapted for a good mounting of linear detectors) and the number of performed tests varied between products, but an approximate comparison of the response time of some different detectors are shown in Table 1. The response time is measured by plunging the detector into a hot tunnel, kept at a specific temperature above the detector’s activation temperature, and noting the time interval between the plunge and activation of the detector. The activation temperature is determined by a slow temperature ramp, 1 °C/min, with the detector mounted in the tunnel. The activation temperatures measured in the heat tunnel were always higher than listed for the product. One reason could be that the listed activation temperatures are specified in an oven with a slower temperature ramp. The response times varied a lot between detectors and for temperatures close to the activation temperature the response times were in general several minutes. For higher temperatures the response times are shorter and the variance between detectors is less significant.

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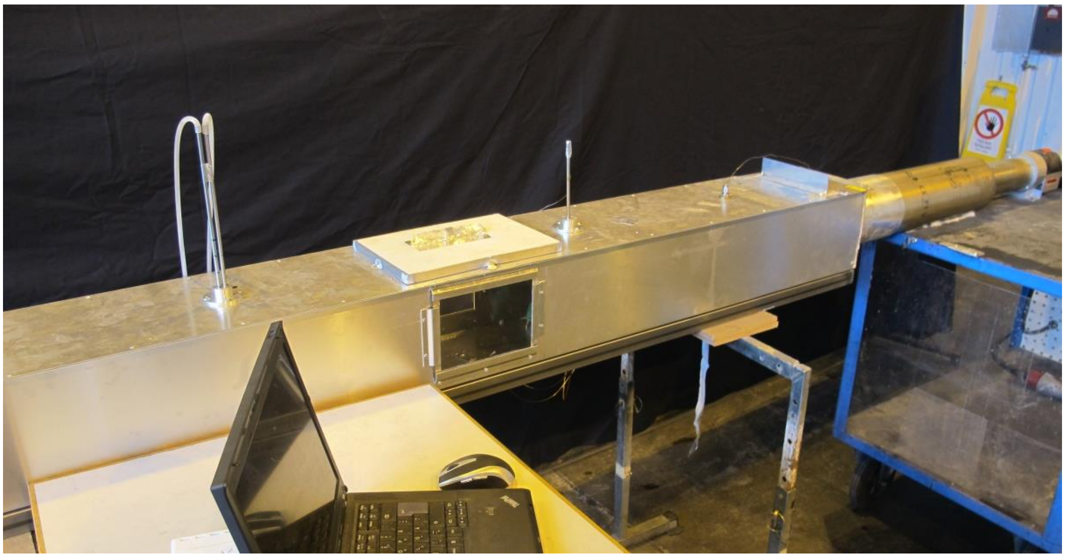

Figure 16. Heat tunnel.

Table 1. Activation temperatures and response times of some different detectors tested in a heat tunnel.

Detector type	Activation temp.	Response time in plunge test approx. 10°C above activation temp.	Response time in plunge test 30-50 °C above activation temp.
Det. 1 (point)	130-150 °C (diff. covers)	4-7 min	2-4 min
Det. 2 (point)	70 °C	~ 1 min	~ 45 s
Det. 3 (point)	140 °C	~ 6 min	~ 30 s
Det. 4 (linear)	190 °C	4-8 min	1.5-4 min
Det. 5 (linear, averaging)	280 °C (10 cm) 180 °C (170 cm)	1-2 min	30-50 s

Heat detectors have also been tested for false alarms against a hot surface. In the test a metal plate was heated by a LPG burner, see Figure 17. A thermocouple was soldered on to the other side of the plate to measure the surface temperature and the detector was positioned at different distances from the hot surface. The temperature of the surface was kept at around 600-650 °C.

Two detectors (det. 3 and det. 5) were highly resistant to this type of false alarm. Shortest distance tested was 5 cm and there were no activation within about 15 min. Most other detectors had to be at least 15 cm away from the surface to not generate an alarm.

All detectors have also been tested in real fire scenarios either in a realistic engine compartment mock-up, as seen in Figure 18, or in simpler setups as seen in Figure 19. Size of fire, fuel composition, airflow, distance to detectors and positions of detectors, either above the fire or beside, have been altered in the tests. Also different kinds of obstructions have been used.

Figure 17. Metal plate heated by a LPG burner for false alarm tests.

The general conclusion from the real fire scenarios is that heat detection is uncertain to occur unless the flames impinge directly on the sensor. Detectors positioned above the fire or where the smoke accumulates could generate an alarm if there was minimal air movement, but with some airflow ventilating and diluting the hot fire gases detection did not occur. The tests also showed that activation due to heat radiation from the flames was hard to achieve, since detectors could be positioned very close alongside the flames without initiating an alarm, however, heat detectors are generally not designed for detection of solely heat radiation. Most fires used in the tests were small fires below 50 kW, but some fires up to 100 kW were also used. Larger fires will produce more heat and consequently be easier to detect. Also the surrounding temperature, which could be much higher than in the tests performed, affects the response time. At last, obstructions affected heat detection by preventing the flames to impinge on the sensor.


Figure 18. Heat detector fire test in an engine compartment mock-up.

Figure 19. Heat detector fire test.

5.2.2 Flame detectors

Flame detection systems were tested primarily in open areas at different distances from the test fires, which included gas burners, liquid pool fires and plastic fires. Some scenarios also included different types of obstructions in front of the fire, exemplified in Figure 20. Obstructions turned out to be a challenge for the systems tested, which was further confirmed in tests conducted in the engine compartment mock-up shown in Figure 18. In general an obscuration of 25-50 % of the flames prevented activation of the detector, however, this is highly dependent on the size of the fire and the distance to the detector. Also the configuration and settings of the detector are important. It is always a balance between sensitivity and the risk of false alarms, which makes the suppliers use different flame detectors and configurations depending on the application. For instance, the detectors that were tested in the project are designed for engine compartments, which resulted in that detection of the fire in Figure 20 (but without obstruction) was not achieved at greater distances than about one meter. Other flame detection systems designed for other applications would most likely detect that fire from tens of meters.

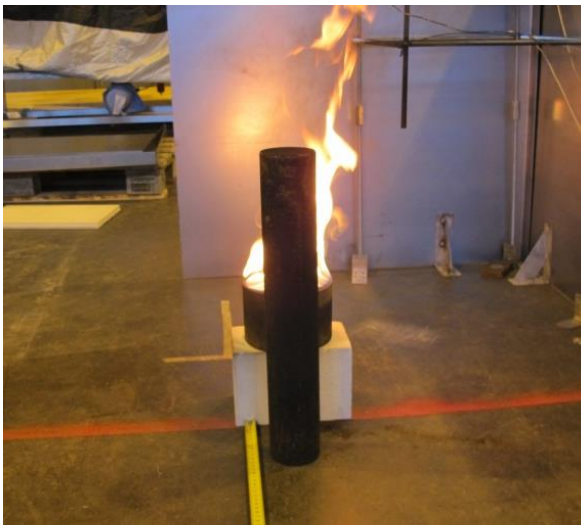

Figure 20. Obstruction in front of a heptane pool fire.

The detectors' field of view were tested, and varied between 30-60 degrees depending on distance to fire and size of fire. The projected area of the sensor facing the fire will be smaller if the detector is rotated away from the fire, decreasing the amount of radiation absorbed. Up to 30° rotation, the reduction of detection capability will be quite small, but a rotation angle above 60° generally reduce the detection capability by more than 50%, meaning that the detector has to be less than half the original distance to the fire.

The propensity of false alarms was tested by exposure to a hot surface and welding. In general, this will not initiate any alarms. Flame detectors are often configured to be sensitive to several different wavelength regions and use the relationship between these regions to differentiate between actual fires and radiation sources considered as false alarms. However, some flame detectors will give an alarm if the change of radiation is great enough, which means that an alarm can be generated if the radiation source is concealed and then suddenly disclosed. Further, this feature can make the detectors irresponsive to slow-growing fires due to that the radiation is compensated for as if it was changes in the background, such as the heating of a hot surface.

5.2.3 Smoke detectors

Smoke detectors are still uncommon for vehicle engine compartment applications and only one aspirating smoke detection system was tested in the engine compartment mock-up. The system performed well, also for high airflows, which is the greatest challenge for detection of smoke. Several different fuels were tested, including plastics, cables, diesel, heptane and E85. E85, producing significantly less smoke, was the only one creating some problems. Notable is that the response time of the detector was not decreased for significantly higher fire loads and rates of smoke produced, indicating that the main contributors to the response time of the detector to be the sampling time and/or the algorithm processing time.

The main issue for smoke detectors has historically been the harsh and dirty environment of an engine compartment. However, this can be managed and tests where smoke detection systems have been installed in different vehicles show that false alarms can be avoided. However, it still poses a challenge and may require shorter service intervals depending on the type of vehicle and environment it is operating in.

5.3 Conclusions

Fire detection systems for vehicle engine compartments use almost exclusively heat as criteria for fire detection today. Both point and linear heat detectors are common and there are several different technologies used. Heat detectors are generally much cheaper than flame and smoke/gas detectors, and provide in general a high level of robustness. As an example of the robustness; dirt and dust rarely have as much impact on heat detectors as for other technologies. Another advantage is that they can be very simple and e.g. not include any electronic circuits at all for activation of the suppression system (see section 5.1.1 above). However, the high ambient temperatures and the airflows in engine compartments put heat detection to a challenge. In general, the flames have to be very close or impinge on the sensor for the fire to be detected. For that aspect, linear detectors have an advantage over point detectors by the coverage of more points in space.

If flame detectors are used they are often used as a complement to heat detection and designed for fast response in case of a spray fire or a large pool fire. The response time is often less than one second if the fire is in line of sight of the detector and sufficiently large. However, obstructions are a challenge and can prevent detection if the fire is not

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large enough. In addition, slow-growing fires are sometimes not detected at all. Flame detectors are not affected by airflow, but can get obscured by dust and dirt on the detector lens.

Smoke/gas detectors have the unique ability to detect smouldering fires and slow growing fires at an early stage. Moreover, the coverage of an engine compartment is more easily obtained compared to heat detectors. However, dirt, dust and exhaust can generate false alarms and the detectors may require shorter service intervals.

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6 Fire detection in bus and coach toilet compartments and driver sleeping compartments (WP5)

The purpose of WP5 was to provide recommendations on what type of fire detection system that should be used and how these systems should be installed in bus and coach toilet compartments and driver sleeping compartments. In July 2014 a new UNECE requirement came into effect which states that excess temperature or smoke shall be detected in these compartments [15]. Therefore, this work provided timely information on the installation of fire detection systems in toilet compartments and driver sleeping compartments.

The work of WP5 and the installation recommendations have been published in SP Report 2014:28 “Fire detection & fire alarm systems in heavy duty vehicles : WP5 – Fire detection in bus and coach toilet compartments and driver sleeping compartments”. The main results and considerations have also been published as a peer-reviewed article in *Case Studies in Fire Safety* [16]. The recommendations are mainly based on full scale fire tests performed in mock-ups of a bus toilet compartment and driver sleeping compartment. A total of 26 different buses and coaches from a variety of suppliers were investigated to obtain input for the construction of realistic mock-ups. Five different fire detection systems were tested: a linear heat detector, a point smoke detector, a point smoke/heat detector, an aspirating smoke/heat detector, and another aspirating smoke detector. These detectors were placed at several different positions in the mock-ups to evaluate how such detectors are best installed. The detectors were exposed to different fire scenarios and different fire sources were used such as: paper hand towels in the trash can, plastics and rubber representing fire in electrical components and cables, and a mattress in the sleeping compartment. In total 18 different full scale fire tests were performed.

The luggage compartment is not explicitly mentioned in the new UNECE requirement, but it is recommended to put detectors there also. In the luggage compartment a wide variety of potential fire sources could be present. From the study it appears that air velocities up to 10 m/s are not uncommon in air streams in the luggage compartment, which makes it important to examine detectors placement based on specific air flows.

The most interesting finding in this work was the large impact of the ventilation fan inside bus toilet compartments. In several fire scenarios the impact of the fan was so great that a fire detector in the ceiling of the toilet compartment would not give a fire alarm in the early stage of a fire.

6.1 Conclusions

Smoke detectors are generally much faster than heat detectors, which is the case in all tests presented in the WP5-report. In the presented tests the fires have developed quite rapidly, but for slow growing fires the benefit of smoke detectors compared to heat detectors would be even greater. However, there are locations where heat detection may be considered, e.g. in the concealed space under the sink in toilet compartments or close to the trash can where the detector is expected to be in the immediate vicinity of the fire. In very narrow spaces and in other circumstances when the detector is close to the potential fire source heat detectors will also react relatively quickly, although smoke detectors will most often still be faster. The benefits of using heat detectors in these

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spaces are that they are usually cheaper and more robust. They may also require less maintenance and inspection than smoke detectors.

In toilet compartments it is common to install a smoke detector in the ceiling, but the tests clearly showed that with an operating fan it could be difficult to detect a trash can fire or cable fire solely with a smoke detector in the ceiling (see SP Report 2014:28 for details of the layout and air flow conditions). However, the fan may be malfunctioning resulting in the smoke being transported upwards and not into the concealed space under the sink where normally the fan is located. In such cases a detector in the concealed space would be of limited use while a detector in the ceiling would be more effective. There might also be other fire scenarios than those tested in this work. Therefore a detector in the ceiling is useful as a part of an integrated detector system. The recommended requirement based on the work presented in the WP5-report is that the detection system should consist of at least a smoke detector in the ceiling and heat or smoke detector in the concealed space of the fan, especially if this space also contains the trash can. For instance, in toilet compartments of airplanes they use heat detection together with an extinguishing bottle above the trash can as a complement to smoke detection in the ceiling. The suppression occurs in this case only locally inside the waste bin.

If smoke detectors are used in many spaces the use of aspirating systems should be considered instead of point smoke detectors. The benefit of this approach is that only one detector is needed and the system samples air from e.g. both the ceiling and other spaces in the toilet compartment. More advanced aspirating systems could potentially also sample air from different locations around the entire bus. An aspirating smoke detector positioned e.g. in the toilet compartment ceiling also has a great advantage in that the detector is hidden and protected. According to the bus operators they have problems with passengers pulling down the detectors, and not even a protective cage around the detector is necessarily sufficient to protect against tampering. In particular it has been noted that smokers are prone to tamper with detectors in toilet compartments. This further supports the use of aspirating systems where the detector is hidden.

It is important to consider whether cigarette smoke should result in a fire alarm or not. Most of the detectors tested did not respond to cigarette smoke, which is at least partly due to the fact that these detectors are designed to have a high resistance to false alarms. In the cigarette smoke scenario, this implies that the obscuration from the cigarette smoke was too low for detection. A cheaper and simpler detector may be more sensitive to cigarette smoke, but could also be more sensitive to e.g. dust. An emergency evacuation on a highway, because of a smoker, induces other risks which should also be taken into account when considering whether the detection system should detect cigarette smoke or not.

Another important design consideration when installing detectors in the toilet compartment ceiling is the need to avoid the air flow from the air inlet. The tests have shown that the detection time may be delayed considerably with the detector positioned in the inlet air flow, up to half a minute in these tests. This difference may be even larger for slow-growing fires.

The tests in the sleeping compartment showed good circulation and fast smoke spread inside the compartment. The time difference between having the detector close to the fire or at the opposite end of the compartment was quite small. However, the results indicate that the detectors should be placed near the ceiling. In addition, the mattress fire source was analysed regarding toxic elements in the fumes. The results showed that the time of evacuation from the activation of a fire alarm until the conditions are immediately dangerous to life and health inside the compartment is approximately 30-60 seconds. However, the response times of the detectors varies depending on position and type.

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Some of the full scale fire tests were also simulated in FDS (Fire Dynamic Simulator). The results showed that computer simulations may be used for detector placement guidance in these kinds of compartments. For complex geometries this tool may be effective for evaluation of where to position the detectors.

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7 Development of international standard (WP6)

The purpose of WP6 was to develop a new test method for fire detection in engine compartments of heavy vehicles that can be implemented as an international standard. This was done on the basis of the information gained throughout the project, such as information of other standards and research in the area (WP1), knowledge of the characteristics and the harsh environment of engine compartments (WP2), knowledge of fire causes, fire scenarios and fire conditions possible in engine compartments (WP3), as well as experience of how detection systems performed in tests and evaluation of different test setups and test scenarios (WP4).

The test method has been published as SP Method 5320 “Test method for fire detection systems installed in engine compartments of heavy vehicles”. The method includes detection performance tests as well as system durability tests. There are two general performance tests conducted in a standardised enclosure with typical engine compartment characteristics; a “system coverage test” and a “response time test”. In addition, heat sensors, flame sensors and smoke/gas sensors are tested separately for activation temperature/sensitivity, false alarm (heat sensors only) and field of view (flame sensors only). The durability tests evaluate the ability of the detector system to withstand corrosion, ageing, temperature variations, vibrations, shocks, electromagnetic interference and intrusion of water and dust.

7.1 Detection performance tests

To ensure the performance and the capability of a fire detection system a few different tests were developed and evaluated. The final version is published in SP Method 5320 and the choices of fire tests and methods are motivated below.

7.1.1 System coverage test

The system coverage test is designed to ensure that the detection system has the ability to detect fires starting in practically every possible location of an engine compartment. The test apparatus, the test fires and their locations were chosen to be the same ones as used in SP Method 4912, in which suppression systems for engine compartments of sizes 2-6 m^3 are tested in a test rig with a gross volume of 4 m^3.

The system coverage test is performed using a total of 13 test fire locations in an environment which holds the same aggravating factors that could be expected of an engine compartment. There is forced air flow through the test apparatus and obstructions simulating e.g. an engine block which both affects detection performance and restricts installation possibilities.

For real applications, it may be argued that one knows the locations of the fire hazards and hence knows where to place the detector to cover the ignition points, but, as covered in WP3, where the fire starts may not be where it grows and reaches a detectable size. Therefore the system should be installed to cover a large enough area or space in order to have a fair chance of detecting a fire at an early stage. The system coverage test is designed to achieve this.

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7.1.2 Response time test

This test is mainly constructed to provide information and to compare the response times of different detection systems to two different fire scenarios; a slow-growing fire and an instant large flaming fire. The requirements assure that a detection system must consist of detectors which by themselves, or combined with other detector types, can detect both slow-growing fires and, with a short response time, instantly large flaming fires.

The slow-growing fire used in the test method is produced from a LPG-burner which starts at 0 kW and steadily grows with 3 kW per minute. The instant large flaming fire is represented by a pool fire using a heptane/diesel fuel mixture.

7.1.3 Heat detection

The activation temperature/response time of heat detectors is determined in a heat tunnel and is of an informative nature; there will be no requirements for at which temperature or rate-of-rise of temperature a detector should activate. There will, however, be requirements on consistency before and after the durability tests.

Heat detectors will also be subjected to a test designed to rate the false alarm sensitivity due to hot surfaces. Detectors will be placed at different distances away from a hot metal surface and depending on the how close to the surface they can be mounted without generating an alarm they will receive ratings of high, medium or low resistance. The rating is purely informative and is to be used as a guideline on where to install heat detectors without producing false alarms.

7.1.4 Flame detection

Flame detectors will be tested to determine their sensitivity. A LPG-burner will be used to produce fires with different heat release rates. The fire will be hidden behind a screen and suddenly be exposed when the test starts. The lowest heat release rate at which the flame detector activates an alarm is documented and used as a comparative value for the verification test following the durability tests.

Flame detectors will also be subjected to field-of-view tests. The heat release rate from the test fire in the sensitivity test is increased by 50% and the detector is rotated vertically and horizontally to determine its field-of-view. This test provides important information for the installation of the system as the sensor will have difficulties to detect fires outside its field-of-view.

Since a flame detector heavily relies on visibility to detect a fire it is important that the lens is kept clear. It is therefore required that the system has an integrated lens supervision to supply a warning signal if the lens is too obscured by e.g. dirt from the engine compartment.

7.1.5 Smoke/gas detection

The sensitivity of smoke- or gas detectors is determined in a smoke tunnel through which the smoke from heated wood sticks is transported. Time to activation and obscuration level at activation is documented to be compared with the verification test after the durability tests.

Smoke/gas detectors rely on the smoke/gas reaching the sensing chamber. It is also important that the sensing chamber in the detector is not contaminated. Therefore it is

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required that smoke/gas detectors are equipped with sensing chamber supervision which shall trigger a warning signal if the chamber is contaminated. It is also required that the detectors use filters, both to avoid false alarms and contamination of the sensing chamber. If the filter is not visible from the outside the detector shall trigger a warning signal if the filter becomes clogged.

7.2 Detection system durability tests

An engine compartment provides a harsh environment for any component installed in it. The temperature is often in the areas around 100 °C and at hot spots it could be considerably warmer. There is water splashing from the road and during the winter months in cold climates there will be road salt added to that. Vibrations from the engine and the ground will also affect the detection system and temperature changes from cold to warm including humidity changes could potentially also cause problems. Further, there is normally a lot of dirt entering the engine compartment which could greatly affect some detection systems. It is important that a fire detection system is durable enough to withstand the environmental factors affecting it without reducing sensitivity or functionality.

Therefore a few different durability tests are included in the test method. The factors which were found to be most important were corrosion, ageing, temperature variations, vibrations and mechanical shock, electromagnetic compatibility (EMC) and ingress from particles and water (IP-classification).

For EMC and IP-classification the test method refers to UNECE Regulation No.10 and ISO 20653:2013 respectively. The detection system should live up to the requirements in UNECE Regulation No. 10 and the lowest allowed IP-classification is IP65[2].

7.2.1 Corrosion

In order to ensure that the detection system withstand the corrosive effects of salt and atmospheric pollutants the system will be subjected to a 3 week exposure in accordance with test method B in ISO 21207.

Following the corrosion test the detection system shall be subjected to the activation temperature or the sensitivity tests related to the specific detector type. It is required to produce a similar result compared to not being subjected to the corrosion test.

7.2.2 Ageing

The system is subjected to an ageing test using both relevant agents that is likely to come in contact with it, e.g. engine oil and vehicle washing chemicals, and a subsequent elevated temperature test (accelerated ageing).

The reason to include both a test for chemical liquid exposure, in accordance with ISO 16750-5:2010, and an elevated temperature test, using the procedure described in chapter 5.13 in ISO 6722-1, is that polymers age differently and are affected both by heat, humidity and different chemicals. It was found important to include the tests using the most common factors which could affect the detection system.

[2] IP65 is only allowed if it is accompanied with a specification that the detection system cannot be pressure washed. Otherwise the system should be classified towards IP6K6K/IP6K9K.

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Following the ageing test the detection system shall be subjected to the activation temperature or the sensitivity tests related to the specific detector type. It is required to produce a similar result compared to not being subjected to the ageing test.

7.2.3 Vibrations, temperature variations and mechanical shock

In order to ensure that the detection systems endure the mechanical stress from vibrations they will be tested against Test VII (Commercial vehicle, sprung masses) in ISO 16750-3:2013 with a temperature cycle either based on the specifications on operating temperatures of the detection system or between -40 °C and 100 °C.

Following the combined vibration and temperature cycling test the detection system shall be subjected to a mechanical shock test in accordance with Chapter 4.2.2 in ISO 16750-3:2013. It is supposed to simulate larger impacts from e.g. curb stones, a hole or perhaps a small collision. For systems intended to be installed in off-road vehicles additional shock tests are required.

Following the vibration, temperature cycling and shock tests the detection systems shall be subjected to the activation temperature or the sensitivity tests related to the specific detector type. It is required to produce a similar result compared to not being subjected to the durability tests.

7.3 Conclusions

SP Method 5320, a test method for fire detection systems installed in engine compartments of heavy vehicles, evaluates performance and durability of the detection system. Fire detection systems tested in accordance with SP Method 5320 can obtain the P-mark, the quality mark of SP approved products, if certification rules SPCR 197 is fulfilled.

In the certification rules, also developed in connection to WP6, an additional requirement in form of a risk assessment is included. The purpose for this is to adapt the installation of the system to the specific engine compartment in terms of specific fire hazards and the prevailing environmental conditions. Air flow, obstructions, fire loads etc. shall be accounted for and thus contribute to ensure that the system design has the ability to cover the identified fire hazards and achieve fast detection regardless of where in the engine compartment the fire originates.

For buses and coaches, SP Method 5320 will complement SP Method 4912 to include both fire detection and fire suppression in the P-mark certification of fire safety systems. As previously done for fire suppression, where parts of SP Method 4912 have been implemented in the European legislation for buses, through UNECE Regulation 107, also parts of SP Method 5320 will form the basis for a proposal of new requirements for fire detection to be implemented in UNECE Regulation 107.

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