Fire detection & fire alarm systems in heavy duty vehicles

WP2 – Factors influencing detector performance in vehicles

Ola Willstrand, Jonas Brandt, Peter Karlsson, Raúl Ochoterena, Vedran Kovacevic

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Abstract

The work presented in this report is part of a larger project about fire detection and fire alarm systems in heavy duty vehicles. The work presented here covers measured data and theoretical background of durability factors influencing fire detector performance and life-span in engine compartments of heavy duty vehicles. The purpose of this work is mainly to provide background information for the overall goal of defining an international test standard. Component requirements set to ensure survivability in an engine compartment will be based on this work. Suitable test methods for different durability factors are suggested and experimental data can be used to define suitable requirement levels. The experimental results consists of measurements on a city bus, on two wheel-loaders, and on a truck operating in an ore mine.

Key words: durability, test methods, vehicles, fire detection, measurements

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Preface

This work was partly funded by the FFI program of the Swedish Governmental Agency for Innovation Systems, VINNOVA. Fire detection systems were provided by Consilium Marine & Safety AB which, along with all support from other co-partners in the project, is gratefully acknowledged.

Summary

This report summarises the results from the second work package (WP2) of the project “Fire detection & fire alarm systems in heavy duty vehicles – research and development of international standard and guidelines”. The purpose of WP2 is to provide measurement data and theoretical background of durability factors associated with the environment in engine compartments of heavy duty vehicles.

The first part of this report (chapter 2) 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 ground 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.

In the last part of chapter 2, the large variation of geometry and ventilation conditions for different engine compartments are discussed. The size differences can be several cubic meters large, as can the differences in open space in the engine compartments. Some compartments are almost completely sealed with no airflow, while others are open or have high air exchange rates.

The second part (chapter 3), 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 discussion and summary of a suitable test method that may be used to verify that the component will withstand the environment.

1 Introduction

In June 2013 a project entitled “Fire detection & fire alarm systems in heavy duty vehicles – research and development of international standard and guidelines” was launched. The project is 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 is to develop an international test method for fire detection systems in the engine compartment of buses and other heavy duty 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 duty 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 are mainly focused on producing background material for the overall goal of defining an international test standard for fire detection in engine compartments, WP6. The second work package, WP2, documented in this report, covers what durability factors that influence detector performance and life span in the engine compartments of heavy duty vehicles. The report includes theoretical background of different durability factors, experimental results and measurements, as well as a suggestion and overview of suitable test methods.

The purpose of WP2 is to provide background information for WP6. The standard proposal, developed in WP6, will include component requirements to secure that the detectors can withstand certain levels of e.g. vibrations, temperature variations, and corrosion. These requirements will be based on the work presented in this report.

This report consists of two major parts: the first half of the report presents experimental results and measurements, and the second half presents a more theoretical introduction to the subject and discusses of suitable test methods.

2 Temperatures, vibrations, particles, and geometry

Fire detection systems installed in an engine compartment have to withstand a rather harsh environment with e.g. high temperatures, vibrations, and dirt and particles. In this environment they have to be able to distinguish between what is a normal environment and what is produced from a fire, and they have to be able to perform even after having been exposed to e.g. gas temperatures of 100°C, dust from a saw-mill, the fumes from an old and poorly functioning two-stroke engine, and driving on cobblestone. In order to get an idea of what a normal environment is for some vehicles, measurements of temperatures, vibrations, dirt deposition, and particle concentration and size distribution were performed on a city bus, wheel loaders and a truck. Last in this chapter there is also a general discussion about geometry of engine compartments and differences in ventilation conditions.

2.1 Measurements on a city bus

The purpose of these measurements was to map the background noise and normal environment inside the engine compartment of a modern city bus for different driving conditions. The measurements include temperatures, vibrations, and particle concentration and size distribution. Furthermore, continuously logging smoke detectors were installed to see their response to this environment. The smoke detectors as well as the particle concentration and size distribution measurement equipment were also used during a range of tests simulating different potential false alarms and fire sources.

The engine compartment of the bus can be seen in Figure 1 (all photos of the bus is in black and white and anonymised, requested by the vehicle manufacturer) and a sketch of the engine compartment is present in Figure 2. Two different optical smoke detectors (one using only red light and one with a dual sensor using both red and blue light) where installed inside a box in the passenger compartment connected with a sampling system drawing air from one of the test points shown in Figure 2 (test point varied with tests). A separate smoke detector (single light) sampled air from three of the test points simultaneously. The sampling rate was about 15 l/min for both systems. Also the Electrical Low Pressure Impactor (ELPI), used to measure particle size distribution and concentration, sampled air from the same point (which varied with tests) as the box with the two smoke detectors.

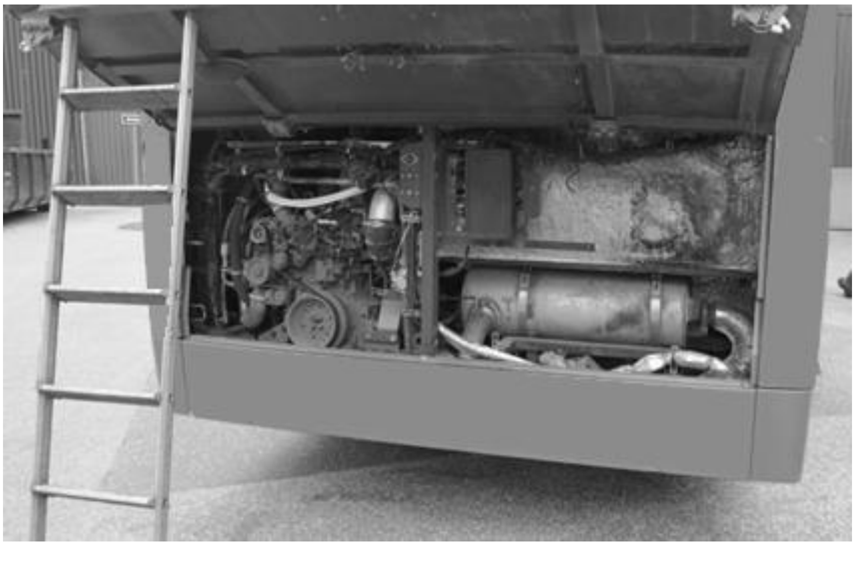

Figure 1. The engine compartment of a modern city bus.

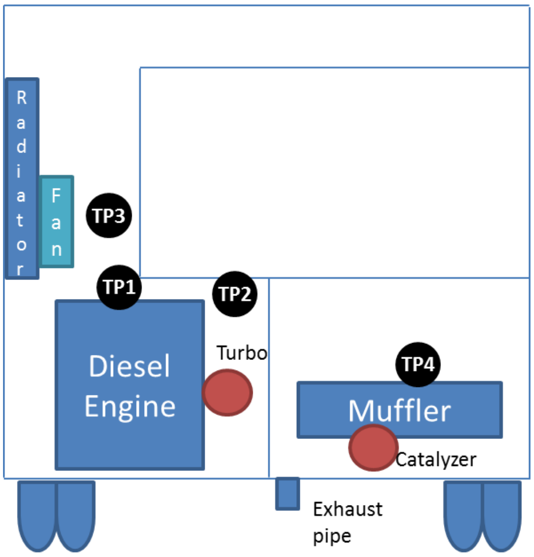

Figure 2. A sketch of the engine compartment in Figure 1 (not to scale). Test point (TP) 1-4 is highlighted.

2.1.1 Measurements during mixed driving conditions

Two similar tests were conducted while driving in an urban area; including driving on highway and on gravel. Measured temperatures for the two runs can be seen in Figure 3 and Figure 4. In the first run there was only one thermocouple soldered on to the surface of the turbocharger, while in the second run there were also one on the surface of the catalyser and one measuring the air temperature on the hot side of the engine. The temperature peak of the turbocharger after 25 minutes in the first run and the first large peak in the second run correspond to acceleration on the highway. In the first test driving on gravel is done between 35-40 minutes after start (start means minute time = 0 in the figures) and in the second test for 10 minutes after 40 minutes from start. The last peak in both runs are the same upward slope back to the starting location. The differences between Figure 3 and Figure 4 is due to that velocity, acceleration, and exact driving route were not the same.

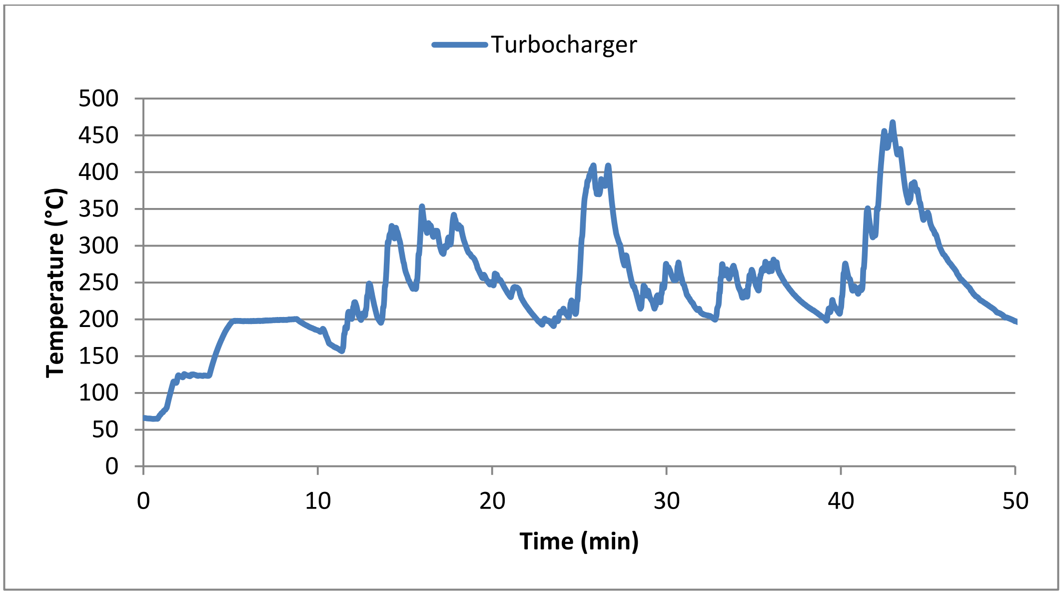

Figure 3. Temperature of the surface of the turbocharger in the first run.

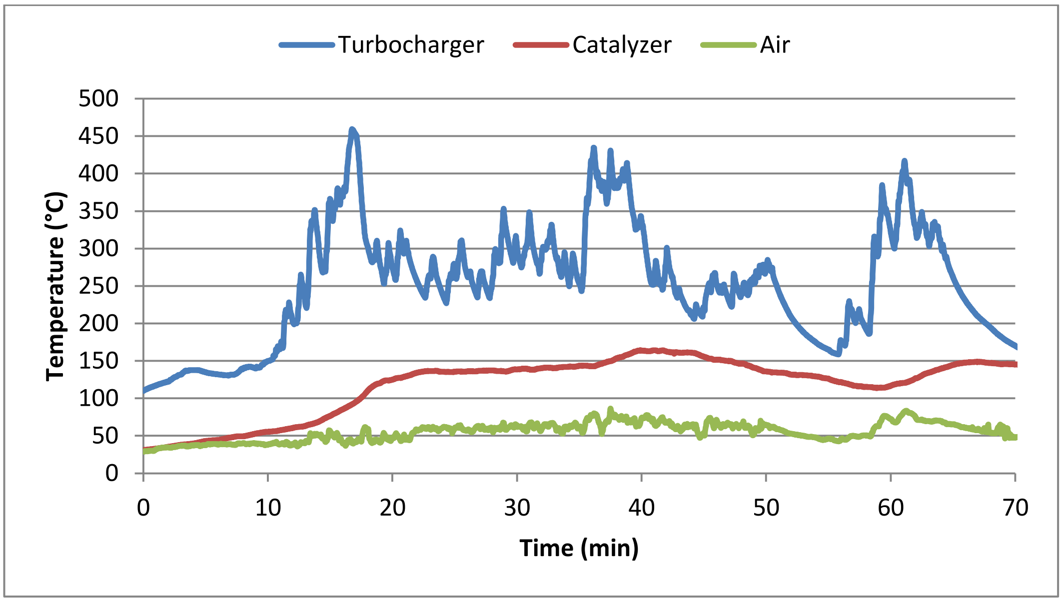

Figure 4. Temperatures of the surface of the turbocharger, the surface of the catalyser, and the surrounding air in the second run. The air temperature is from the hot side of the engine close to the turbocharger.

Vibrations were only measured in the first test and the result can be seen in Figure 5. The accelerometer was fastened on the body frame in the engine compartment and a sampling rate of 20 Hz was used. For each sampling interval the peak value of the vector sum of acceleration in x, y and z directions were registered. However, calibration of the accelerometer shows that for vibrations with frequencies over 50 Hz the accelerometer cannot register correct peak values of the acceleration. This means that for very short pulses/chocks the peak value registered could be lower than the correct peak acceleration. The peak values after 35 minutes seen in Figure 5 correspond to driving on gravel.

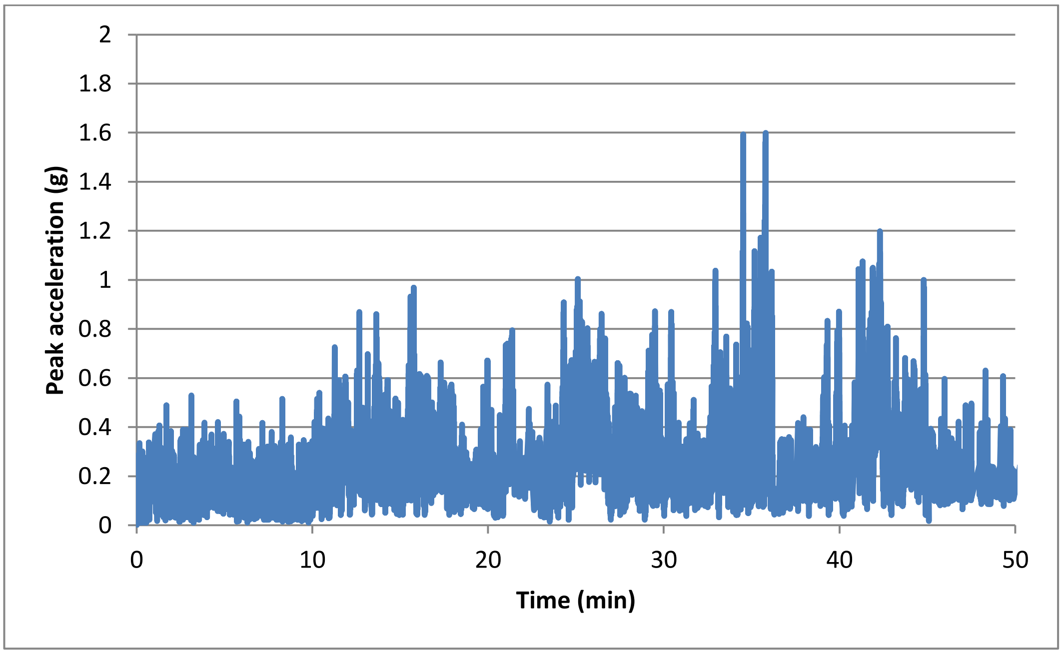

Figure 5. Vibrations are presented as peak acceleration as a function of time. The acceleration is measured in gravitational acceleration (g). Data is from the first run.

Figure 6 and Figure 7 show the particle concentration and distribution recorded by the ELPI for the two runs at TP1 and TP2. These measurements were started a little later than the vibration and temperature measurements, but before the bus started to move. In the first few minutes the bus is idling. The figures show particle matter (PM) with diameter less than 10 µm, 1 µm, and 0.1 µm. This means that if all three graphs are identical there are only particles less than 0.1 µm. The difference between purple and green lines are the number of particles between 0.1-1 µm, etc. The figures show that there are mainly particles smaller than 1 µm present and for the first run most particles are smaller than 0.1 µm. It is interesting that much higher concentrations are found in the beginning of both runs, despite different driving conditions in the two tests. Contrary to expectations driving in the gravel area, see Figure 8, did not give much higher particle concentrations. In the first test driving on gravel is done between 35-40 minutes after start and in the second test for 10 minutes after 40 minutes from start. The reason could be either that the dust contains lower concentrations of larger particles or because the dust did not reach the test points chosen.

Optical smoke detectors mainly respond to particles larger than 0.1 µm and the smoke detectors sampling from the same test point as the ELPI did not give any response at all. The detector sampling from TP2, TP3, and TP4 simultaneously gave a significant response in the beginning of the second test, but did not reach alarm levels. There was no response on the gravel dust.

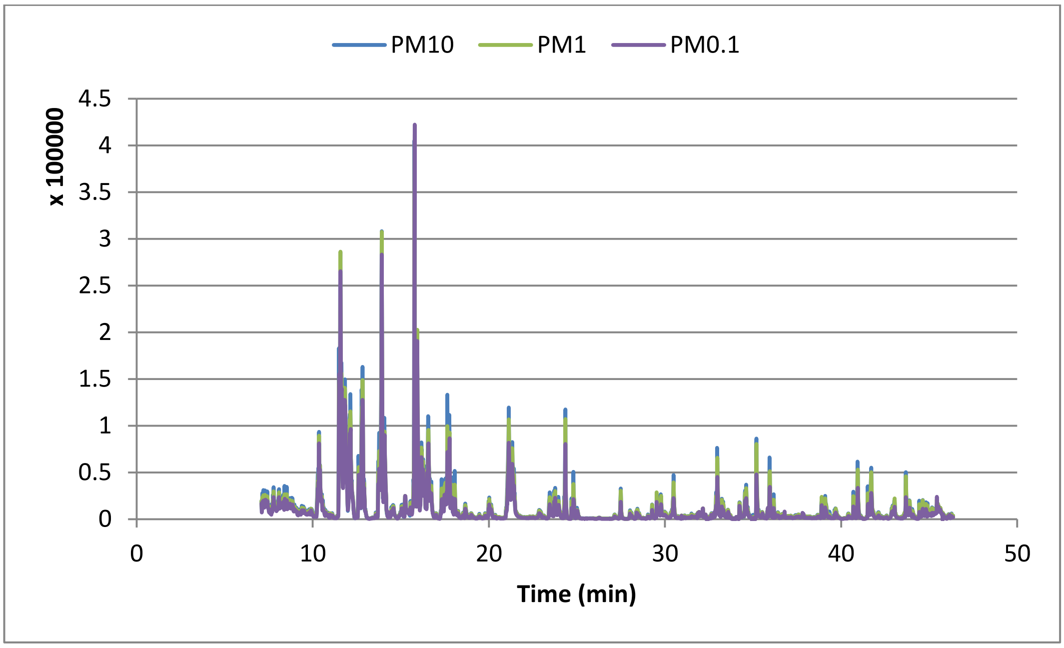

Figure 6. Particle matter measured by the ELPI in the first run at TP1 (Figure 2). PM10 is particle matter with diameter less than 10 micrometres, PM1 less than 1 micrometre, and PM0.1 less than 100 nanometres. The number of particles are per cubic centimetre.

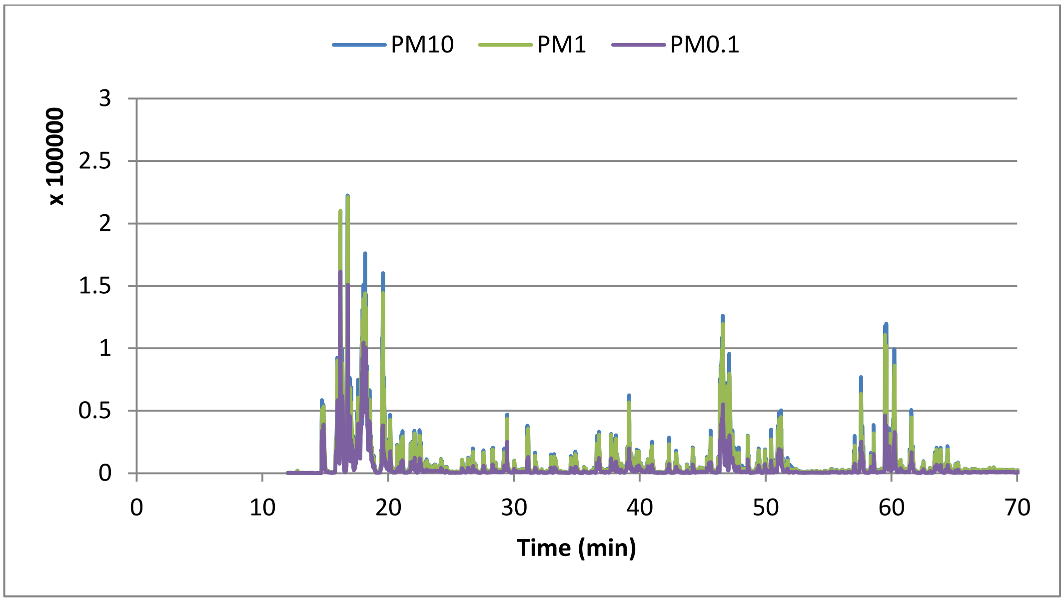

Figure 7. Particle matter measured by the ELPI in the second drive at TP2 (Figure 2). PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

Figure 8. City bus driving in the gravel area.

2.1.2 Potential false alarms and fire sources

Different potential false alarm sources for smoke detectors and potential fire sources were simulated in different ways when the bus was stationary. The tests are presented in the following sections.

2.1.2.1 **Exhaust**

Exhaust is a potential false alarm for smoke detectors and high levels may accumulate in e.g. tunnels, garage, and in heavy traffic. To simulate high levels of exhaust the exhaust was manually led back into the engine compartment, see Figure 9. Comparison tests were performed to see the difference between having high levels directly led into the compartment and high levels outside of the compartment that is entering the engine compartment through the radiator and fan.

Figure 9. Exhaust is led into the engine compartment directly (right photo) or through radiator from the bus (upper left photo) or from an external truck (lower left photo).

The particle matter measured when leading back the exhaust from the bus itself can be seen in Figure 10. The high levels around minute 54 (the time axle is cut off because the ELPI run continuously between tests) correspond to when the exhaust is led back to the engine compartment directly, and the small levels around minute 53 to the left in the figure correspond to when guiding the exhaust to the radiator from the outside. There were no response from any of the smoke detectors and comparisons to Figure 6 and Figure 7 shows that the levels were not higher than during normal driving. In this test the bus was idling.

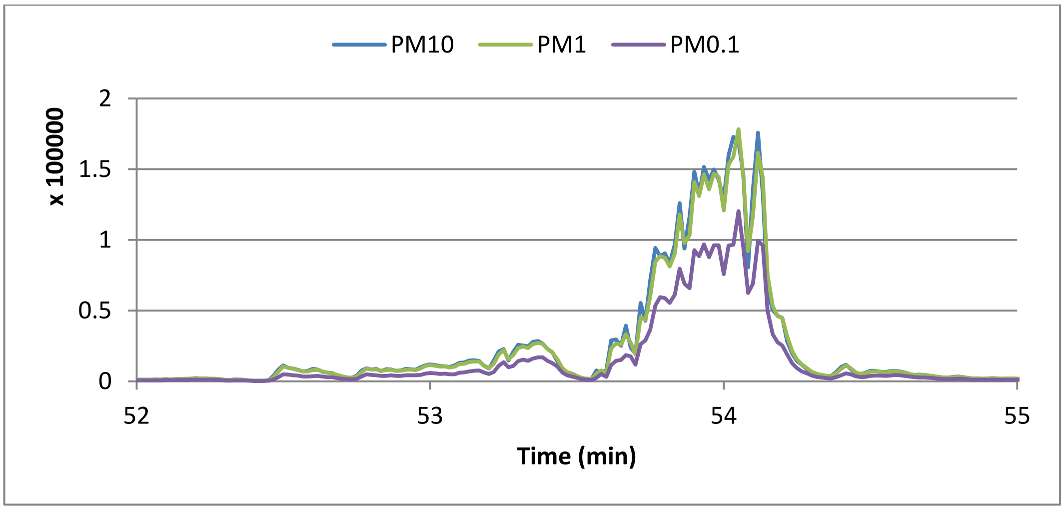

Figure 10. Particle matter measured in exhaust from the bus at TP1 (Figure 2). PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

In Figure 11 the particle matter is measured when exhaust is led from a truck to the radiator of the bus, see Figure 9. The peaks between 76-78 minutes to the left in the figure correspond to when the truck is started and shut off in intervals to create bad combustion. On the right hand side between 80-82 minutes the truck was started and then idling. The number of particles in the peaks is quite high but the duration is short (<10s) and the level is back to what is seen in Figure 10 shortly thereafter. The smoke detectors (sampling either from TP2 only or from TP2, TP3, and TP4 simultaneously) registered the peaks but were far from alarm levels. The highest response came from the detector sampling from multiple points, and it is expected that the highest concentrations are found at TP3 where the exhaust from the truck enters the engine compartment.

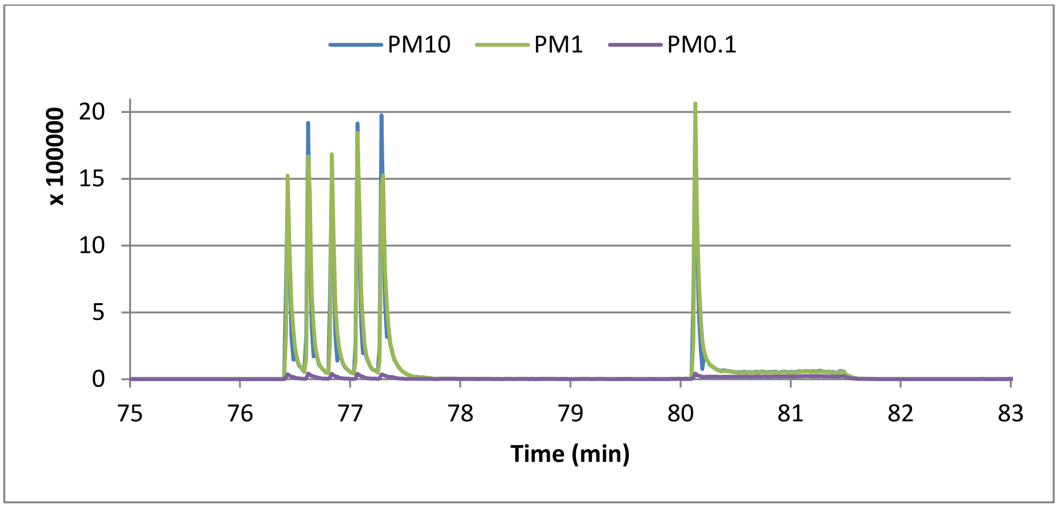

Figure 11. Particle matter measured in exhaust from a truck at TP2 (Figure 2). PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

2.1.2.2 Water steam

A high pressure water spray was directed towards hot components in the engine compartment to create some water steam as a potential false alarm, see Figure 12. None of the smoke detectors gave any response. The ELPI was not used since it cannot measure droplets, only particles.

Figure 12. High pressure water spray directed towards the engine compartment.

2.1.2.3 Smoke from potential fire sources

Smoke was generated from potential fire sources by heating different materials with a standard hotplate, see Figure 13 where the hotplate was placed above the catalyser. The hotplate was set at a temperature of 470°C before any material or liquid were applied on the hot surface. In Figure 14 and Figure 15 the measured data is from heating cables. Four, approximately 20 cm long and diameter 15 mm, insulated conductors were laid tightly to each other on the hotplate. In the first test the cables (and hotplate) were positioned on the left side of the engine block beneath the fan, see Figure 2. The ELPI measured particle concentration at TP2, quite far from the smoke source, and the concentration levels seen in Figure 14 are lower and with a larger portion of small particles than in the second test, see Figure 15, with the hotplate and cables placed above the catalyser and with sampling at TP4, which is relatively close to the position of the hotplate. The smoke detector sampling from TP2 had a very low response, and it was only the detector sampling from multiple points that registered smoke levels high enough to cause an alarm in the first test. However, in this test the duration of the peak was too short to actually trigger an alarm.

In the second test (Figure 15) the cables were positioned at the catalyser, and the ELPI and the smoke detectors sampled air from TP4, right above the cables. In this test the concentrations of larger particles are significantly higher (because the test point is closer to the fire source) and the smoke detectors gave alarms at the same time as the ELPI registered the larger peak of particles (after minute 115 in Figure 15).

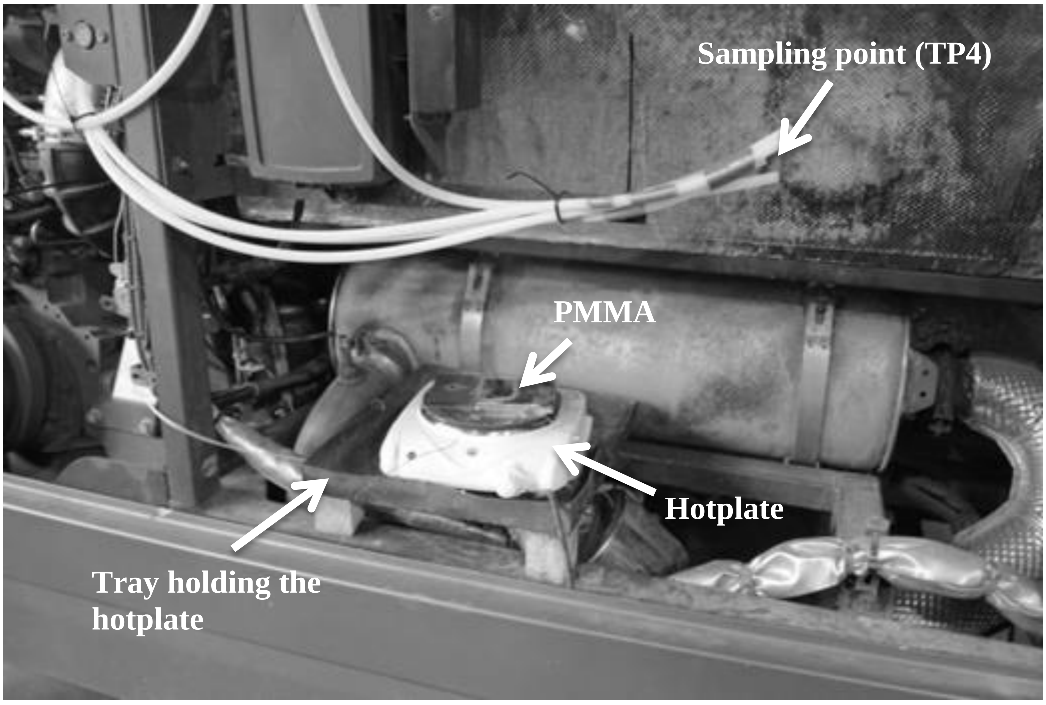

Figure 13. PMMA on a hotplate positioned at the catalyser.

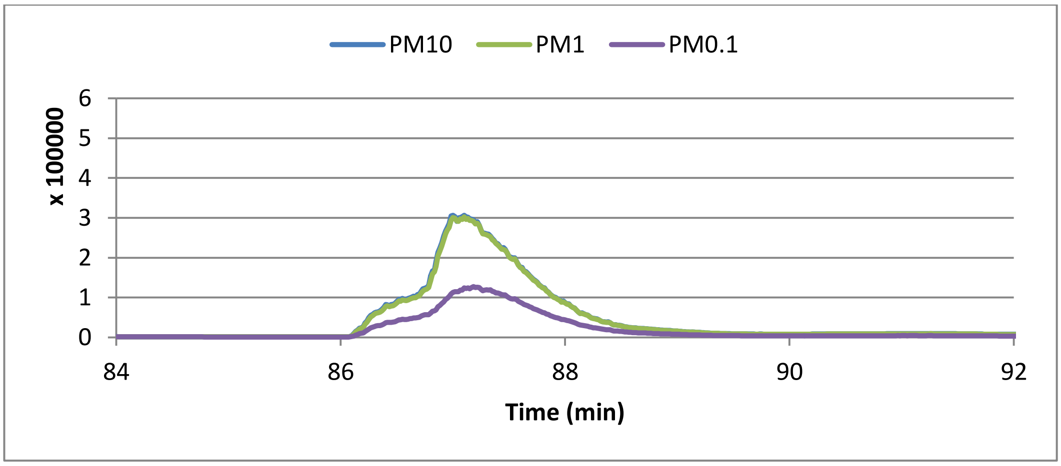

Figure 14. Particle matter measured at TP2 (Figure 2) in test with cables on a hotplate positioned on the left side of the engine block beneath the fan. PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

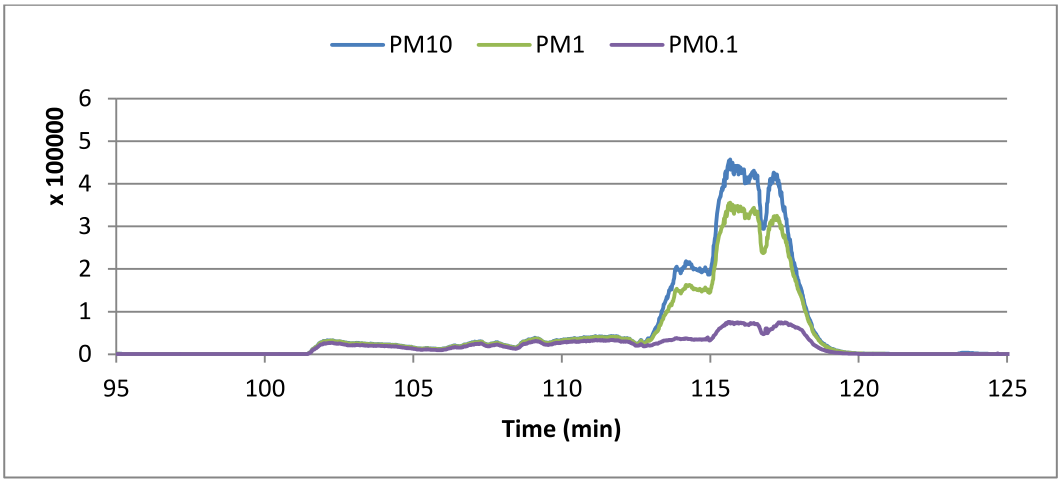

Figure 15. Particle matter measured at TP4 (Figure 2) in test with cables on a hotplate positioned at the catalyser. PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

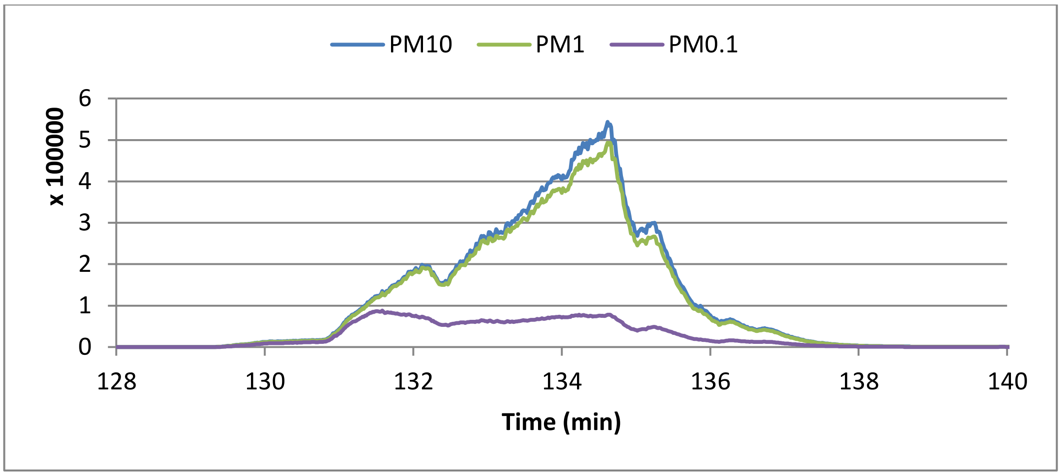

Figure 16. Particle matter measured at TP4 (Figure 2) in test with PMMA on a hotplate positioned at the catalyser, see Figure 13. PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

Figure 16 shows a similar test to the second test with the cables but with PMMA instead of cables. PMMA is used in many fire tests and is commonly used as reference material. The segment of PMMA was approximately 10 × 10 cm and 10 mm thick. The fire detectors had a similar response like they had to the cables.

With the same setup with the hotplate as in Figure 13 additional tests were performed with diesel and a glycol-water mixture dripping on the hotplate producing vapour. Approximately 1 dl of liquid was used in total. In these tests the detectors gave alarms very fast (the ELPI was not used since it cannot measure droplets) and as can be seen in Figure 17 the amount of smoke produced was considerable.

Figure 17. Diesel spray on a hotplate inside the engine compartment.

2.1.2.4 Smoke from a fire outside of the engine compartment

A diesel pool fire was positioned outside of the engine compartment, see Figure 18. An external fan directed the smoke towards the radiator and fan of the bus and the ELPI measured particle matter at TP4. The results are presented in Figure 19. The particle concentration measured is quite high, higher than for the tests conducted inside the engine compartment, but there were very low responses from the detectors. One reason to that is probably that the duration of high concentrations was short and that there were less particles over 1 micrometre compared to the tests associated with Figure 15 and Figure 16. The smoke detector sampling from multiple points, including TP3, gave the largest response.

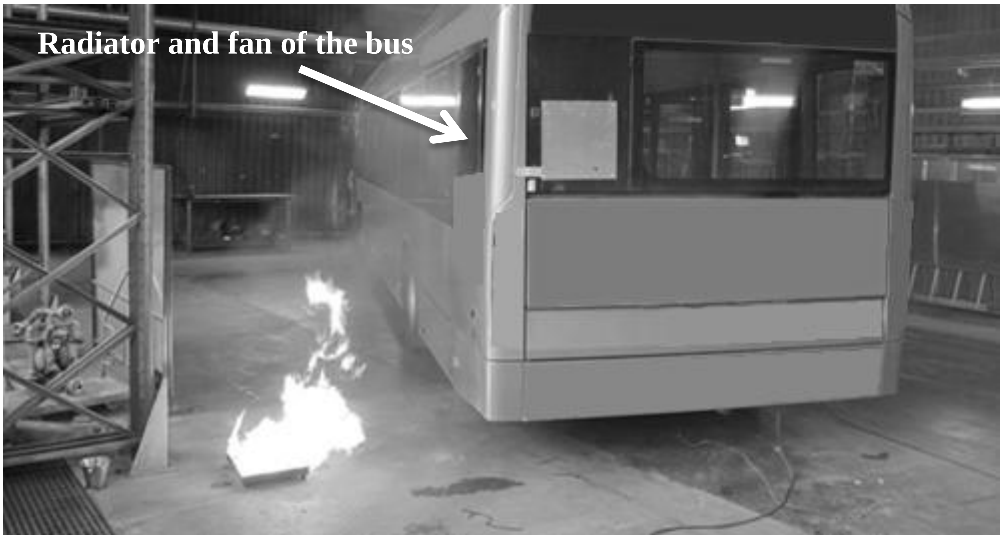

Figure 18. Smoke from a diesel pool fire on the outside of the engine compartment.

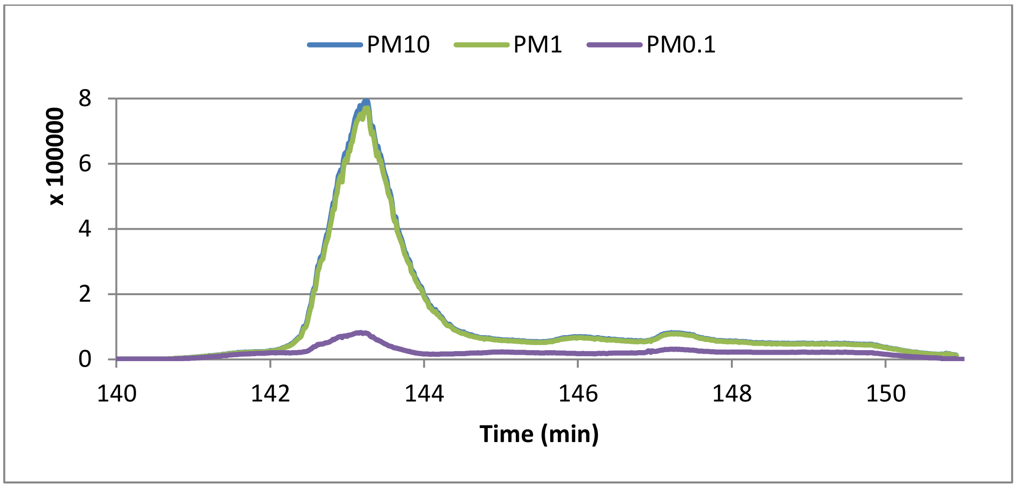

Figure 19. Particle matter measured at TP4 (Figure 2) in test with a diesel pool fire on the outside of the engine compartment, see Figure 18. PM10, PM1, and PM0.1 are explained in Figure 6. The number of particles are per cubic centimetre.

2.2 Measurements on wheel loaders

Measurements of temperatures and vibrations were performed on two different wheel loaders (of the same brand) to get a picture of normal background activity (no particle measurements were performed on these vehicles). The test procedure consisted of short cycles of intensive loading and driving for reaching realistic conditions of the engine components and hydraulic systems. The test were conducted on a test track and ambient temperature were about 3 °C.

Temperature measurements were made by installing thermocouples soldered on to the surfaces of the engine components and auxiliary systems or freely suspended for registering the air temperature inside the engine compartment at points of interest.

For vehicle #1 the temperatures of the following points were registered:

1. Turbine casing of the turbocharger.
2. Intercooler.
3. Surface of the aftertreatment system.
4. Surface of AC compressor.
5. Exhaust pipe.
6. Monoblock.
7. Air temperature (hot side).
8. Air temperature (cold side).

For vehicle #2 the temperatures of the following points were registered:

1. Turbine casing of the turbocharger.
2. Air pipe downstream the intercooler.
3. Surface of the aftertreatment system.
4. Pipe between turbocharger and aftertreatment system.
5. Exhaust pipe.
6. Exhaust multiple.
7. Air inlet downstream air filter.
8. Air temperature (hot side).
9. Air temperature (cold side).

Temperature plots are shown in Figure 20-Figure 21. As expected, the temperature of the turbine casing is highest in each of the cases and varies as function of engine load. The remaining temperatures commence stabilising after around thirty minutes.

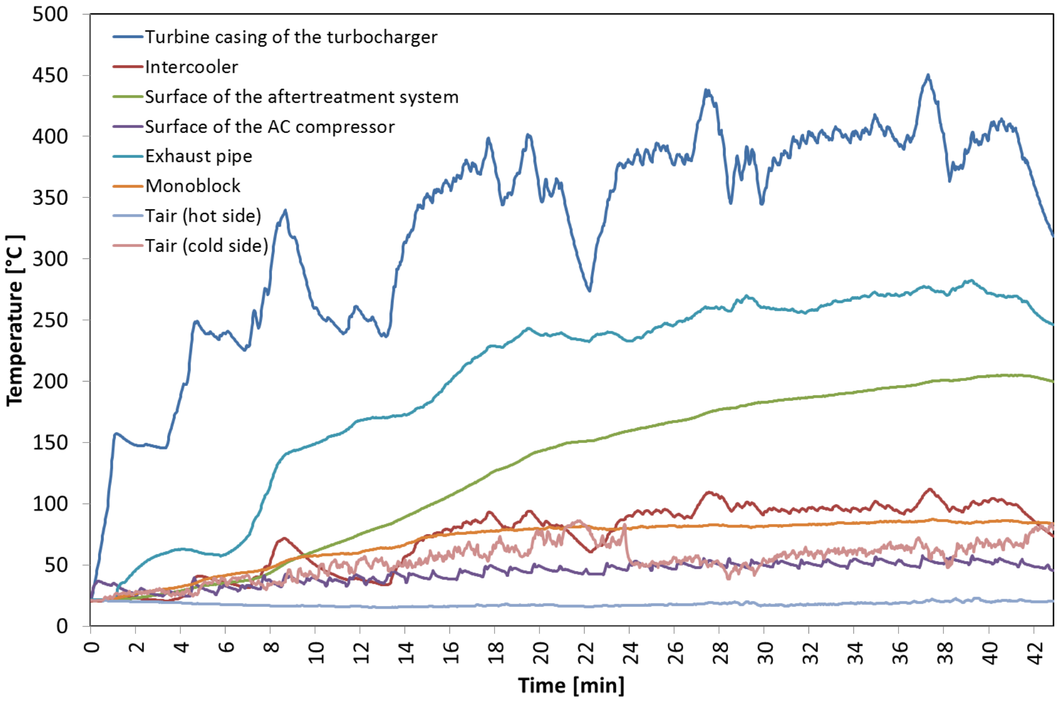

Figure 20. Temperature measurements for vehicle #1.

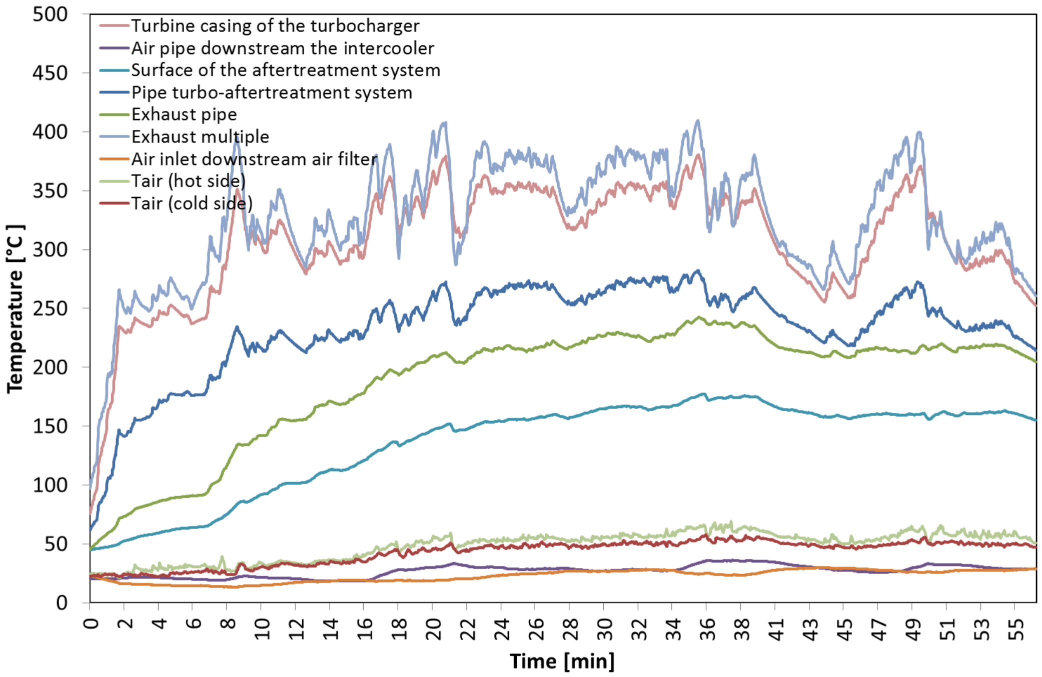

Figure 21. Temperature measurements for vehicle #2.

Vibration intensities were measured by installing a three axis accelerometer onto the chassis of the machines inside the engine compartment and logging data continuously at a sampling rate of 20 Hz. It was the same accelerometer as used for the bus. A plot of the vector sum of acceleration in x, y, and z directions from the test with vehicle #1 can be seen in Figure 22.

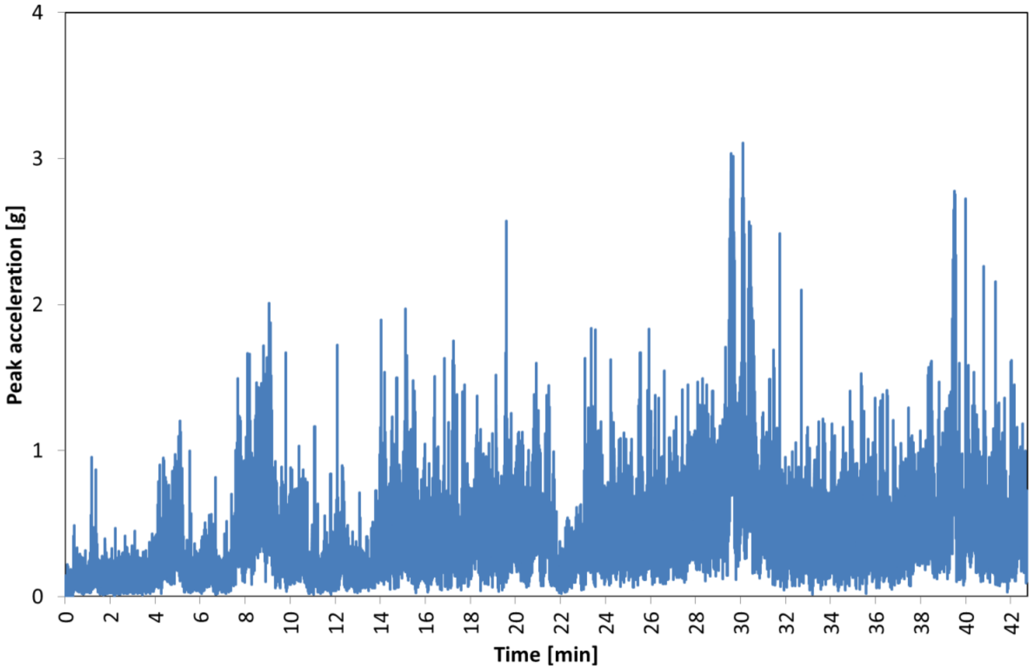

Figure 22. Vibration intensities as a function of time. The peak acceleration is measured in gravitational acceleration (g). The sampling rate was 20 Hz.

2.3 Measurements on a truck in an underground ore mine

Measurements of temperatures, vibrations, and particle deposition where performed in the engine compartment of a truck operating in an underground ore mine. The truck operated as it usually do transporting ore down in the mine. In addition, smoke detectors were installed to see their response in this environment, which is one of the harshest environments they may be used for. The test was conducted during several weeks. However, the length of the measurements varied depending on what was measured.

Temperature measurements were made by installing 0.5 mm type K thermocouples in the engine compartment. Air temperatures were registered at three different points; at the rear end of the engine block, close to the manifold and turbocharger, and in the ceiling. The thermocouples were positioned at least 5 cm from nearest surface. These points are indicated by arrows in Figure 23. Temperature variations during 24 hours for the three different positions are shown in Figure 26-Figure 28. However, temperatures were registered during a two week period and for the thermocouple positioned rear of the engine block the complete data is plotted in Figure 29. Thermocouples were also soldered on to surfaces of some different engine components, e.g. the turbocharger, manifold, and exhaust pipe. The thermal imaging photo in Figure 25 indicate that these surfaces will be much hotter than the surrounding components and when the vehicle is running the temperature of these surfaces can in fact be at least 400-600 degrees Celsius. However, these temperature measurements were affected by small current disturbances in the chassis and unfortunately unreliable, and therefore not presented in this report.

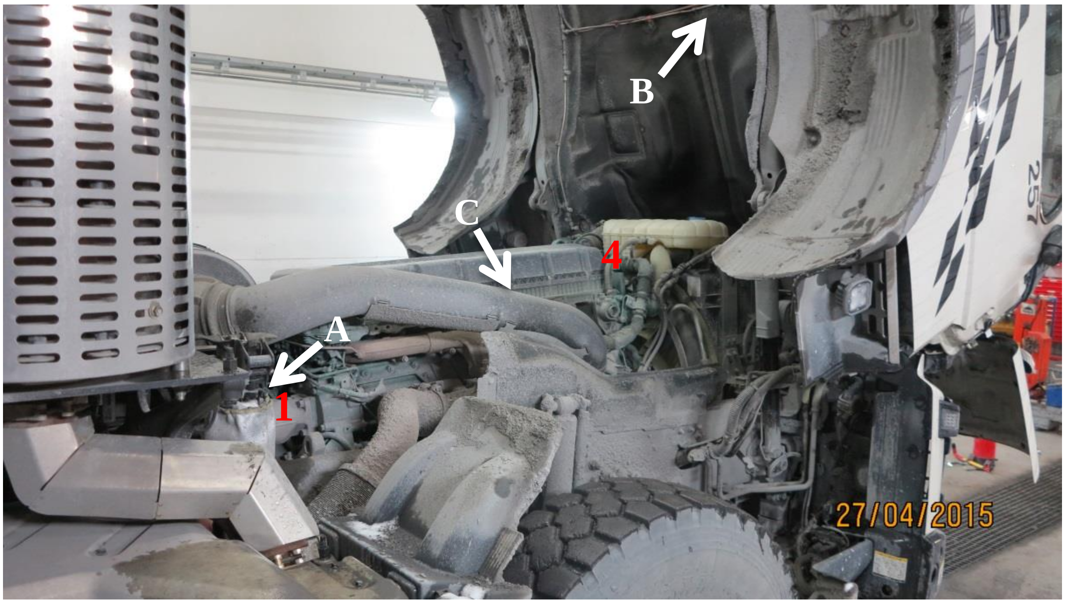

Figure 23. Hot side of the engine compartment. Arrows and letters indicate positions of thermocouples and numerals indicate positions of smoke detectors.

Figure 24. Cold side of the engine compartment. Numerals indicate positions of smoke detectors.

Figure 25. Thermal imaging photo of the engine block and turbocharger (similar angle as in Figure 23).

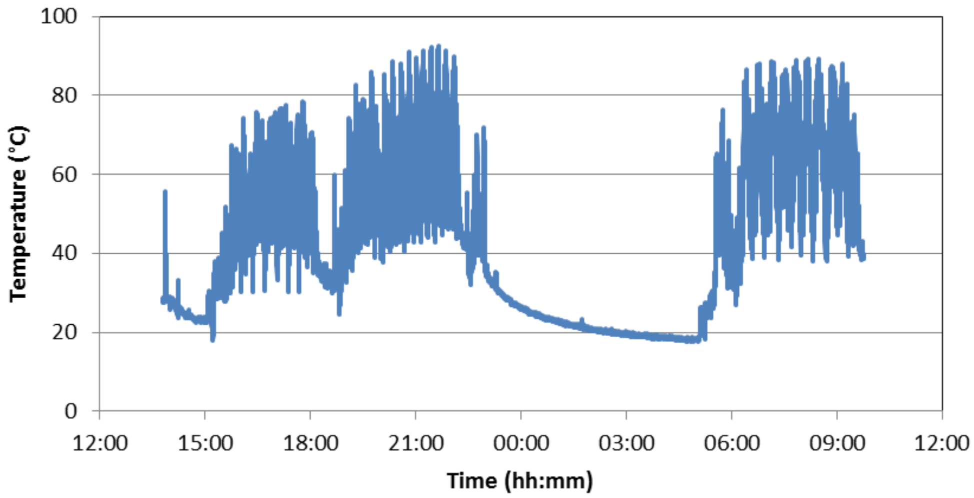

Figure 26. Air temperature measurements at the rear end of the engine block (position A in Figure 23).

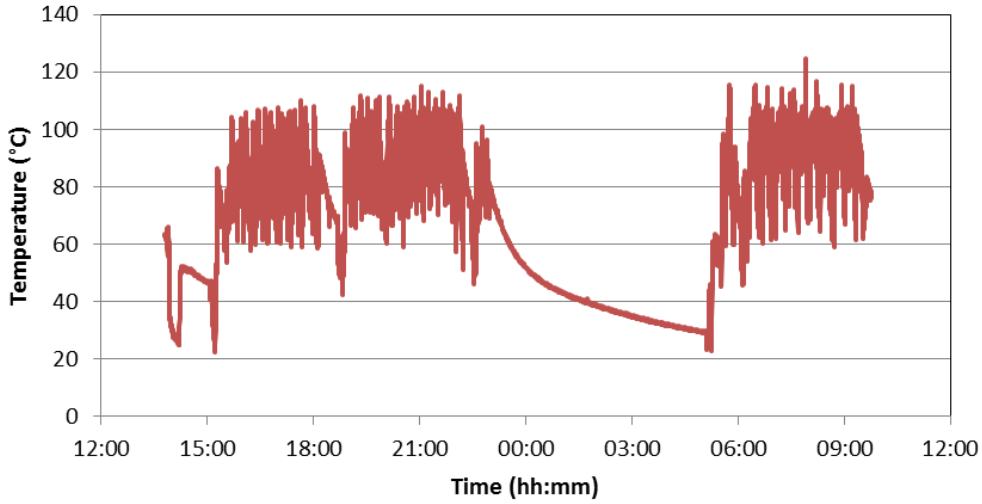

Figure 27. Air temperature measurements in the ceiling of the engine compartment (position B in Figure 23).

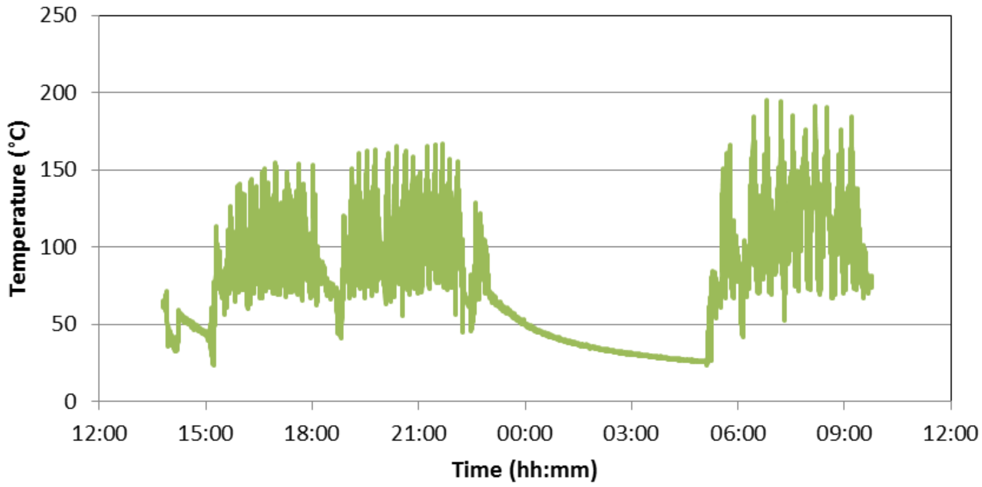

Figure 28. Air temperature measurements about 20 cm above manifold and turbocharger (position C in Figure 23).

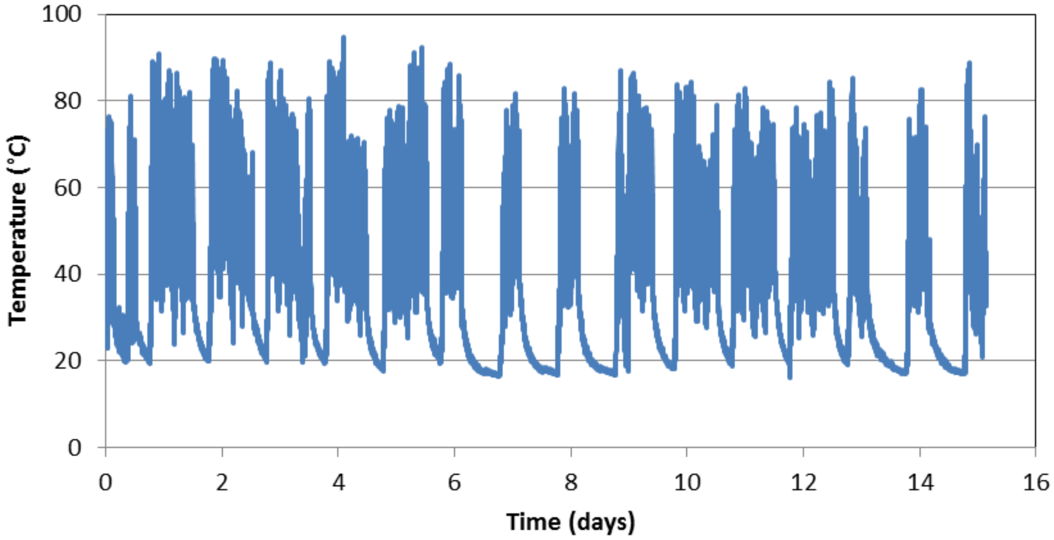

Figure 29. Air temperature measurements at the rear end of the engine block for a two week period (position A in Figure 23).

Vibration intensities were measured during nine hours by installing a three axis accelerometer onto the body frame of the truck and logging data continuously at a sampling rate of 4 Hz. For each sampling interval the peak value of the vector sum of acceleration in x, y and z directions were registered. It was the same accelerometer as used for the bus which means that for very short pulses/chocks the peak value registered could be lower than the correct peak acceleration. The data is presented in Figure 30. The truck was parked between 18:10-18:40 and after 23:00, as can be seen in the figure. Small vibrations at these times could be due to vibrations in the ground generated by e.g. other vehicles. It could also be due to imprecise compensation of the gravitational acceleration.

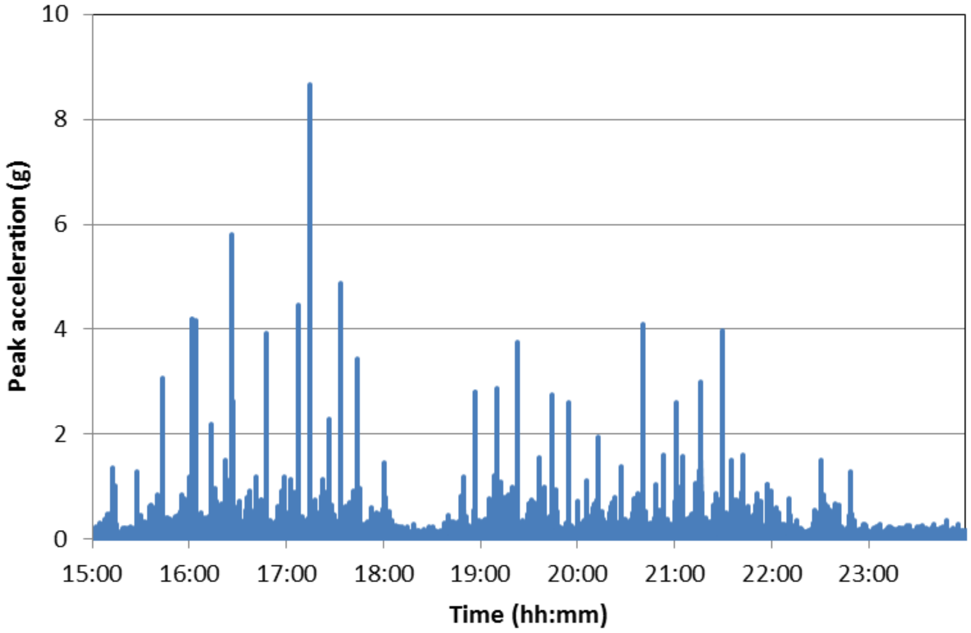

Figure 30. Vibration intensities as a function of time. The acceleration is measured in gravitational acceleration (g). 4 Hz sampling rate.

Deposition of dirt, oil, and other contaminants on surfaces and its influence on light absorption was studied by means of placing optical blanks of CaF_2 in the engine compartment. That kind of deposition is critical for the performance of optically-based systems, such as flame detectors. The glass windows were placed in the engine compartment of the truck as well as in the engine compartment of a wheel-loader, also operating in the mine, for comparison. Positions were representative for where flame detectors may be positioned to monitor the area around the engine block. The glass windows were removed after three months, and plots of spectrally resolved light transmission through the contaminated optical blanks are shown in Figure 31. The discontinuous plot is due to that different setups are used for the UV-vis-NIR (ultraviolet-visible-near infrared) region and the IR (infrared) region. The plots indicate that light transmission in the UV-visible region is reduced more than in the IR region by deposition of contaminants, if compared with uncontaminated CaF_2 (Figure 32). A general conclusion is also that the engine compartment of the wheel-loader seems to be cleaner than the engine compartment of the truck. This is expected since the engine compartment of the wheel-loader is more sealed.

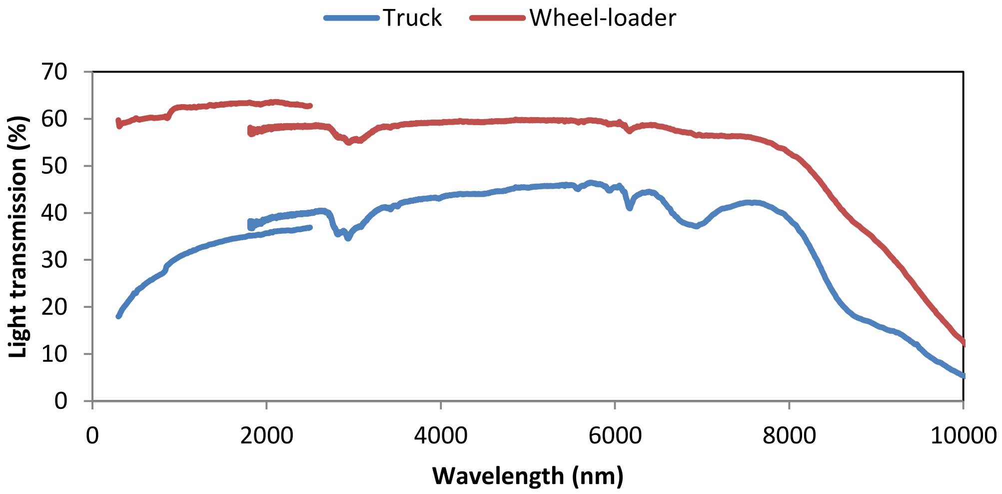

Figure 31. Spectrally resolved transmission of light through optical blanks of CaF_2 for assessing deposition of contaminants.

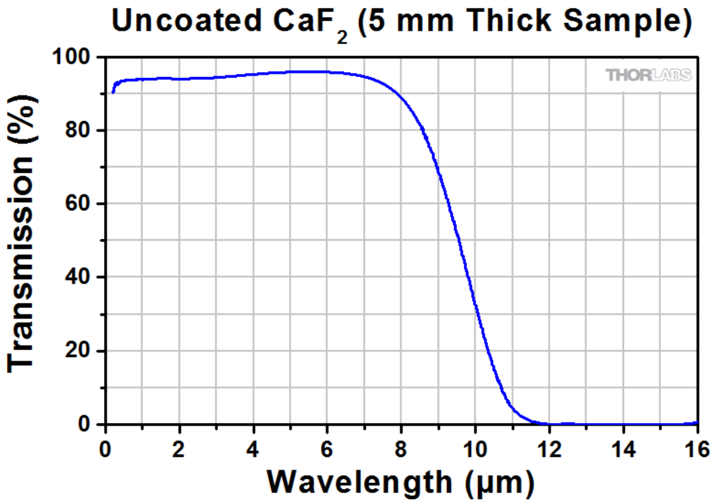

Figure 32. Transmission of light through uncontaminated optical blanks of CaF_2. [1]

There were four smoke detectors installed in the engine compartment, indicated by numerals in Figure 23 and Figure 24. All four detectors were of the same type and based on the light scattering principle. Plots of the smoke signal (scattered light measured in the smoke chamber) as a function of time for all four detectors are shown in Figure 33. Detector 4 was saturated after a couple of days and Detector 3 was saturated after about a month, while Detector 1 had just slightly increased the background level after two and a half months. Detector 2 was malfunctioning after about 18 days. However, these detectors are normally placed in clean environments and were only tested to see how fast they would be saturated in such a harsh and dusty environment. In a realistic situation they would be protected by means of e.g. filters and preferably be placed outside of the engine compartment sampling air from points of interest.

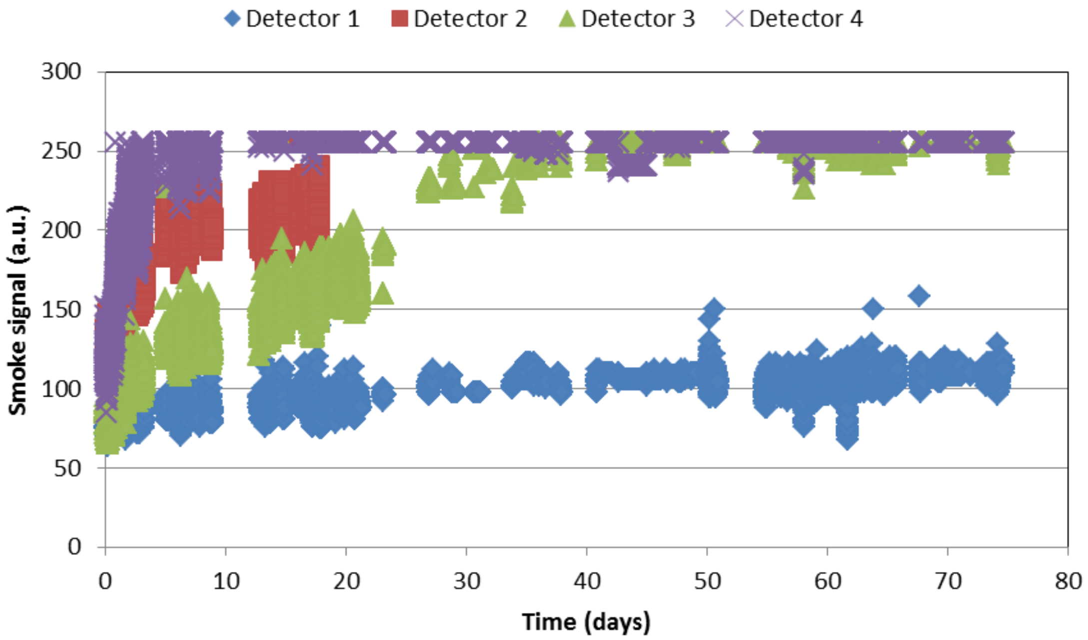

Figure 33. Output from four smoke detectors as a function of time. Detector numbering is related to positions in Figure 23Figure 24.

2.4 Geometry and ventilation

The geometry of an engine compartment and the ventilation rate along with the air velocity inside the compartment greatly affects both a fire and the possibilities to detect it. Different methods of detection are differently affected and where e.g. a flame detector's performance won't be affected by the ventilation it will be by the geometry and possible obstructions in the engine compartment. It is therefore relevant to get an overview of the geometries and ventilation rates of heavy vehicle engine compartments. However, the variations are large and every model from every vehicle manufacturer look different, see e.g. Figure 41 to Figure 49 in Appendix A.

Some of the engine compartments are completely cluttered with almost no open spaces within them while some have 50 % open space. Some are almost completely open with only side walls around them and lacking both floor and a complete roof while some are almost completely sealed with only a few ventilation holes. The positions and sizes of these ventilation holes also vary. Ventilation holes may be filtered, especially if air is flowing into the compartment through them when the ventilation fan is set to draw air into the compartment and one wish to not draw dirt into the engine compartment. Fans can also push air into the compartment and then the ventilation need not be filtered. Some vehicles use reversible fans and may either push or suck air into the compartment. Some have a high ventilation rate with big fans moving air through the engine compartment while some have almost no air movement at all inside them. Some have a volume of less than 1 m^3 while the bigger ones could be 10 m^3. Some have walls between the cool side of the engine and the warm side, keeping heat sensitive parts away from heat radiators, such as the exhaust system and the turbo charger, while others only make sure to keep sufficient distance to the hot surfaces.

All these variations have effects on how the fire products spread and reach the fire detection system. Hence the choice of system and the setup of the system need to be adapted to the geometry and ventilation of each different engine compartment design.

3 Durability factors and suitable test methods

There are several physical factors influencing the durability of fire detectors mounted in engine compartments of heavy duty vehicles. Some phenomena are a result of chemical reactions within the environment, such as the oxidation of metals that results in corrosion. Other occurrences are temperature rise due to the combustion process in the engine or vibrations and shocks due to uneven roads or harsh road bumps as well as the motions caused by the rotating parts inside the engine block itself. Furthermore, all electronic devices or installations influence each other when interconnected or close to one another. In order to minimise the interference they need to be electromagnetically compatible with one another. All these physical factors influence the lifespan of fire detectors in different ways.

In this chapter, the most frequent physical phenomena occurring inside an engine compartment and those that are of most importance will be presented. Descriptions of each of them will be made and the corresponding theory of each one will be highlighted. Certain test methods that are deemed appropriate in order to assure that the fire detector can sufficiently withstand these physical influences will be suggested.

The information in this chapter has also been published as a Master's thesis by Kovacevic [2].

3.1 Corrosion

Solids such as metals, ceramics, and polymers can all corrode, and they all do so in different ways. When iron come in contact with chemical elements such as water and oxygen they form hydrated iron oxides, also known as rust. Ceramics are relatively insensitive to corrosion but can become susceptible if the material is subjected to certain acids. Polymers do not corrode in the same way as metals but instead they progressively degrade if they are exposed to inorganic substances or a combination of water, moisture, and heat. When polymers are degraded by moisture or heat, the process is often termed "ageing". [3]

Corrosion can be classified as "wet" or "dry". Wet corrosion refers to when a liquid, in most cases water, combined with air or other gaseous compounds comes in contact with a material. Dry corrosion is a result of the reaction between materials and high temperature gases. Corrosion can occur through direct chemical reactions, i.e. when water and air physically comes in contact with the material, or by electrochemical reactions. It is important to note that corrosion only occurs on the surface of materials. [3]

Corrosion has many different forms and some are explained further in the following sub-chapters.

3.1.1 Uniform corrosion

This is the most common type of corrosion as it is caused by chemical or electrochemical reactions that result in the entire exposed material surface to deteriorate. This corrosion type causes the greatest destruction to the material but it is, however, considered to be a safe form of corrosion, as it is predictable, manageable and often preventable. Uniform corrosion is often termed "atmospheric corrosion". [3, 4]

3.1.2 Localised corrosion

Localised corrosion targets a specific area on the material surface, unlike uniform corrosion. It can be classified as one of three types, as seen below: [3, 4]

- **Pitting** – pitting corrosion leads to small holes or cavities in the material as a result of localised corrosion of a small area on the material surface. This area produces a localised galvanic reaction and becomes anodic (electrically positive), while the rest of the remaining material becomes cathodic (electrically negative). The small holes or cavities function as stress risers which can lead to failures of the material. This type of corrosion can be difficult to detect because the affected areas are very small and may be hidden.
- **Crevice** – this type of corrosion arises at specific locations, such as under gaskets or linings. A crevice has to be large enough such that the corroding substance can enter, but narrow enough to ensure that it remains stagnant. If there are acidic conditions present in combination with a reduction in oxygen, it can accelerate the corrosion process at these locations. Due to where this corrosion arises it can be hard to detect and prevention can be difficult.
- **Filiform** – filiform corrosion occurs under painted or plated surfaces when water breaches the coating. The corrosion starts at small defects in the coating but can rapidly spread and cause structural weakness in the material.

3.1.3 Galvanic corrosion

This type of corrosion can occur when two different metals are located together in the presence of a corrosive electrolyte, as is often the case in an engine room due to many different materials being mounted close to one another and being repeatedly exposed to salt, water, and air during winter time. An electrolyte is a substance which forms ions in an aqueous solution, for instance a combination of salt and water. The material which is the anode is the sacrificial metal, since it is the one that oxidises. The anode corrodes and deteriorates faster than it would alone while the cathode corrodes slower than it would otherwise. For galvanic corrosion to occur the following three conditions must be fulfilled; electrochemically dissimilar metals must be present, the metals must be in electrical contact and they must be exposed to an electrolyte. Electronics can be subjected to galvanic corrosion as two dissimilar metals are often in contact with one another in electrical circuits. This can sometimes be avoided if the bimetals are coated with other non-corrosive materials, such as phenolic, and if noble metals are introduced in the electrical circuits, such as gold. [3, 4]

3.1.4 Environmental cracking

Environmental cracking is a corrosion process that can result from a combination of environmental conditions affecting the metal, such as chemical, temperature, mechanical influences etc. This corrosion type can lead to stress corrosion cracking (SCC) and corrosion fatigue. [3, 4]

- **SCC** – Cracks can be created on the surface as the material is subjected to tensile stresses and temperature variations. The chemical environment that causes SCC is often one which is mildly corrosive to the material otherwise. Therefore, the material can appear bright and shiny while being filled with microscopic cracks. Hence, it is common for SCC to go undetected prior to failure. Furthermore, SCC can grow rapidly and is hard to control. SCC is difficult to avoid and once it has started, it usually ends in unexpected failure of the material.
- **Corrosion fatigue** – Corrosion fatigue is, simply put, the mechanical degradation of a corroded material under cyclic loading conditions that induce cracks in the

material. Cyclic loading refers to vibrations, temperature fluctuations, impacts, etc.

3.1.5 Intergranular corrosion

Intergranular corrosion is a chemical or electrochemical attack on the grain boundaries of a material, in most cases metals or metal alloys. This occurs because of impurities in the metal, which tend to exist in higher numbers near grain boundaries. The boundaries are often more vulnerable to corrosion than the bulk of the metal. [4]

3.1.6 De-alloying

In some alloys, a specific element will be corroded. This is called de-alloying, as that element acts as the anode and vanishes with time leaving the alloy corroded. The most common type of de-alloying is the de-zincification of brass, where the end-product in such cases is a deteriorated and porous copper. [4]

3.1.7 Fretting corrosion

Fretting corrosion is a result of repeated wearing, weight or vibration on an uneven, rough surface. When the surface is subjected to the cyclic variations it results in pits and grooves on the surface. This corrosion type is found in rotating and impact machinery, bolted assemblies and bearings. It can also be found in surfaces exposed to vibrations during transportation. [4]

3.1.8 High-temperature corrosion

High-temperature corrosion is a type of corrosion that can take place in machinery coming in contact with hot gases containing certain contaminants. Some fuels contain vanadium compounds or sulphates which have low melting points. During combustion these can form certain mixtures of melted salts in gaseous forms that are highly corrosive. These are especially corrosive for alloys that are normally resilient to corrosion, such as stainless steel. Almost all materials oxidise and corrode at high temperatures. The difference in what separates them in how they corrode is the rate of corrosion and the nature of the corrosion products. Oxidation, which is by far the most common form of high-temperature corrosion, of a material results in scaling, loss of material and changes in its physical properties. High-temperature corrosion is not restricted to be due to the gaseous phase as solid ashes and salt deposits contribute to the corrosive effect. Gaseous corrosion attack is not limited to only oxygen, as sulphur gases, carbon oxides and many other elements all attack materials in different ways. [3, 4]

3.1.9 Suitable test method

Corrosion tests can be performed in many ways but the best choice is often to simulate an artificial environment that resembles the environment that the product of interest is exposed to in reality. As degradation of metals can take many years, the test is often accelerated in order to make the results feasible. Furthermore, corrosion of metallic materials with or without corrosion protection is influenced by many environmental factors, as stated earlier. The importance of these factors may vary with the type of metal and with the type of environment. Laboratory tests are designed to simulate the effects of the most important factors that enhance the corrosion of metallic materials. The accelerated corrosion test methods are designed to simulate and enhance the environmental influence of exposure to an outdoor climate where salt contaminated conditions and corrosive gases from a moderately aggressive traffic environment occur which may promote corrosion.

The chloride ions that vehicles are exposed to in general are mainly sodium chlorides, NaCl, (simply known as table salt) that come from sea winds and de-icing salts on the roads during the winter. The corrosive gases are generated by gas emissions from vehicles and can often be found in the traffic air pollution but also as leakage gases from the combustion process inside the engine. Thereby, the engine compartment is exposed to both internal and external corrosive gases. The gases that have the most corrosive effect are those which give rise to a low pH value, such as nitrogen oxides, NO_x, and sulphur oxides, SO_x. [5, 6]

The test method ISO 21207 [6], see below, is especially suitable for assessing the corrosion resistance of sensitive products with metals, e.g. electronic devices, used in traffic environments. The method is used to assess the corrosion resistance of products in environments where there is a significant influence of chloride ions and of corrosion-promoting gases. It especially applies to metals and their alloys, metallic coatings (anodic and cathodic), conversion coatings, anodic oxide coatings, and organic coatings on metallic materials.

3.1.9.1 **ISO 21207**

The test specimen is subjected to a test cycle containing two parts. The first part of the test cycle is neutral salt spray testing for 2 hours in a mist of water containing a 5% mass fraction sodium chloride solution at 35 °C, followed by drying for 22 hours in standard atmospheric conditions. The second part of the test cycle is exposure of the specimen for 120 hours in a test atmosphere containing a mixture of corrosive gases. The volume fractions of the gases are 1.5×10^{-6} NO_2 and 0.5×10^{-6} SO_2 at a relative humidity of 95% and temperature of 25 °C. This is followed by drying the specimen for 24 hours at standard atmospheric conditions. One test cycle thereby corresponds to one week’s exposure. [6] The test could be conducted for a period of 6 weeks, corresponding to 8 years in reality.

3.2 Ageing

Ageing is a natural mechanical phenomenon that takes place in any type of environment. Examples of ageing of a material can be due to corrosion, obsolescence, weathering, heat and so forth. It is defined as a gradual process in which the properties of a material, structure or system, change over time or with use due to interaction with its surroundings. Polymers, for instance, are susceptible to negative material property changes if subjected to high temperatures. Therefore, it is of interest to set viable requirements for polymers subjected to temperature variations as the operating temperature in engine compartments are high. However, the high temperatures will probably not have a noticeable impact on the mechanical properties of metals and alloys during the vehicle’s useful lifetime. [7]

It can be hazardous if the degradation process is not managed in a controlled manner, especially in operations where the polymeric components are key components in the machinery itself, as is the case when the fire detector in the engine compartment is in the form of a pressurised plastic hose. If the ageing process of that plastic is accelerated due to the different operating conditions inside the engine compartment, the degradation of the material might cause a bad surface finish, leading to lessened mechanical strength in the material and eventually a small penetration in the hose. This will cause the pressure to decrease, mimicking a fire that has melted the hose, and consequently the result will be a false alarm or a dysfunctional detector. Furthermore, wires in electronics are insulated with plastics which prevent conductors from coming in contact with one another and thus preventing short circuits. If these plastic insulation were to age faster than accounted for, short circuits may indeed become a reality which can have critical impacts on vehicle safety. It is therefore important to recognise which physical factors influence the ageing of polymers and connect them to the physical occurrences in engine rooms. [7]

There are many forms of ageing processes. Four types of ageing processes that are relevant for polymers are listed in their respective sub-chapter below.

3.2.1 Thermal ageing

Thermal degradation refers to the chemical and physical processes in polymers that occur at elevated temperatures. Higher temperatures accelerate most of the deterioration processes that occur in polymers such as oxidation, chemical attacks and mechanical creep. Oxidation is often considered to be the most serious problem when using polymers at higher temperatures. The influence of temperature on the oxidation processes will depend on the chemical structure of the polymer. Oxidation at elevated temperatures is called thermo-oxidation. Thermo-oxidation is initiated by the reaction of free radicals with oxygen to form peroxide radicals. All polymers contain these free radicals due to their polymerization and processing history but the amount of free radicals can be increased by interaction with light or ionizing radiation. Once formed, the peroxide radicals undergo slow reactions that break down the polymer chains. The overall degradation process will normally involve a relatively long induction period during which little degradation is noted. At the end of the induction duration, there is a rapid increase in degradation leading to a major reduction in the mechanical properties of the polymer. The induction period is temperature sensitive and is reduced considerably at elevated temperatures and is in most cases regarded as the functional lifetime of the polymer. [7]

In engine compartments, one of the most common situations that polymers are likely to experience is prolonged exposure to elevated temperatures during the operation and lifetime of the vehicle. The Arrhenius equation is often used for estimating the lifetime of polymers. It is particularly useful for accelerated tests as it allows results from short-term tests conducted at higher temperatures to predict long-term exposures at lower temperatures. The Arrhenius equation is

$$K(T) = A\mathrm{e}^{-\frac{E_\mathrm{A}}{RT}}$$

where $K(T)$ is the reaction rate of the process, E_A is the activation energy, R is the universal gas constant, T is the absolute temperature in Kelvin and A is a constant called the frequency factor of the reaction. The Arrhenius equation may be used prior to testing in order to approximate how long the ageing duration or the ageing temperature of the experimental test should be to be considered viable, instead of guessing the exposure duration or temperature beforehand.

3.2.2 Weathering

Weathering, also known as photo-oxidation, of polymers denotes the chemical and physical changes that occur when radiation is absorbed by a polymer. Photo-degradation is initiated by solar radiation and results in the absorption of UV radiation by the material. Though, other climatic factors such as heat, moisture and air-borne pollution all influence the mechanisms of degradation and the subsequent results of ageing. The intensity of the UV radiation decreases with increasing depth in the material. Therefore, the reaction tends to be a surface degradation process. Either way, there is an important balance between UV radiation, oxygen diffusion and temperature. During dark periods, i.e. during night time or if the polymer is enclosed in a dark space, some recovery of the surface can occur. [7]

Since engine compartments are not subjected to high concentrations of solar radiation, photo-oxidation will be considered not likely to occur.

3.2.3 Chemical degradation

Chemical ageing is often a result of hydrolysis, i.e. by cleaving the chemical bonds of the polymer after contact with fluids. Chemical attacks on polymers involve specific chemical reactions between the polymer and water, acids, or alkalis. A hydrolysis process between a compound and water is seen in Figure 34. By chemical degradation, the material has its molecular weight reduced due to polymer chain scission. This can lead to a reduction in toughness or worse – fracture strains. Furthermore, stress is known to accelerate the chain scission process and to enhance the rate of fluid uptake. [7]

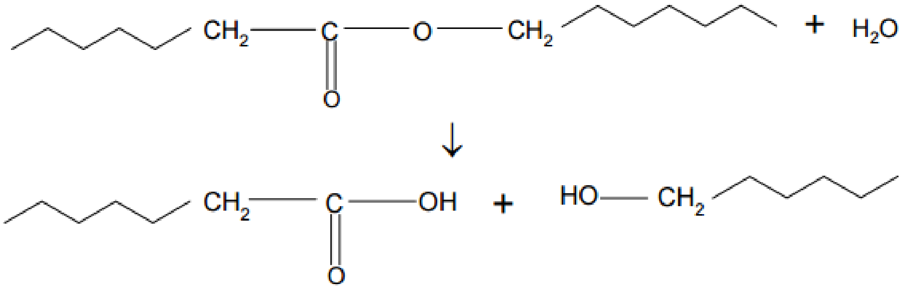

Figure 34. Hydrolysis process of an ester being exposed to water. [7]

3.2.4 Biological degradation

Biological degradation is the least common form of degradation for polymers as most thermoplastics are resistant to microbiological attacks. No predictive techniques for the life expectancy of commonly used polymers due to biological degradation have therefore been developed. [7]

3.2.5 Suitable test method

When speaking of the testing procedure of material ageing the most common methods are accelerated tests. These tests simulate a certain timespan that will reflect the actual usage time of the product. Bearing in mind that the polymeric products are mounted in an engine compartment, which is subjected to large variations in temperature during the vehicle’s operational use, accelerated thermal tests of polymers are the best suited and will be further considered. However, not all polymers can be tested in the same manner. Some materials, such as polyamide, are quite resistant to high temperatures and weathering but can be very susceptible to chemical exposure. When polyamide comes in contact with water or other chemicals it is prone to having its molecular bonds cleaved, resulting in polymeric chain scissions. This effect will only be seen if subjecting the polymer to a test involving them being placed in baths that contain different fluids with variations in temperature. These tests are similar to the *Hot air and cold water shock test* as well as the *Cold and boiling water shock test* as described in sub-chapter 3.3.3.1. Therefore, if the product specification for the fire detector states which type of polymer that is the main polymer in the material composition of the product, consideration to this alternative when choosing the test method for ageing should be taken into account. In the test method ISO 6722-1 [8] presented below, the thermal ageing of polymeric products is highlighted.

3.2.5.1 **ISO 6722-1**

This test method applies mostly to plastic insulations on electrical wires in electronic devices, as is also present in fire detectors. It ensures that a long exposure to high temperatures and variations in pressure will not cause any deviation in the electrical performance of the device, such as short circuits due to flaws in the plastic insulation of the wires. However, this test method and test verification can also be applied to other polymeric hoses and cables, e.g. the case where the fire detector is a pressurised plastic hose that melts when a fire erupts. Exposure to low and high temperature are used in this test method, as polymers are susceptible to both of these in different ways. Typical failure modes of accelerated thermal ageing tests are mechanical fracture, melting, deformation, embrittlement, oxidation, loss of optical properties due to overheating, non-functional device due to degradation and short circuits.

The tests are conducted in a test chamber that resembles an oven. The air exchange in the oven should either be natural or by pressure and should enter the chamber in such a way that it flows over the surface of the test specimen and exits at the top of the oven. There should be a minimum of 8 and a maximum of 20 complete air changes per hour at the specified ageing temperature in the test chamber. The test specimen should be tested in powered off mode. [8]

Verification procedure

If the polymer is a cable insulator that protects the electrical wires, the following verification test is used to verify that the cable insulation is capable of withstanding the required rated voltage.

A test specimen, both cable and insulation, of a minimum length of 350 mm with 25 mm of insulation from each end of the specimen stripped off, should have its ends twisted together to form a loop. Thereafter, a non-conductive container is partially filled with salt water containing 3% mass fraction sodium chloride, NaCl, with the twisted ends of the test specimen emerging above the bath. The test specimen is immersed in the fluid as shown in Figure 35 for a minimum of 10 minutes after which a test voltage of 1 kV AC should be applied using a 50 or 60 Hz AC voltage source. The test voltage should be applied for one minute. [8]

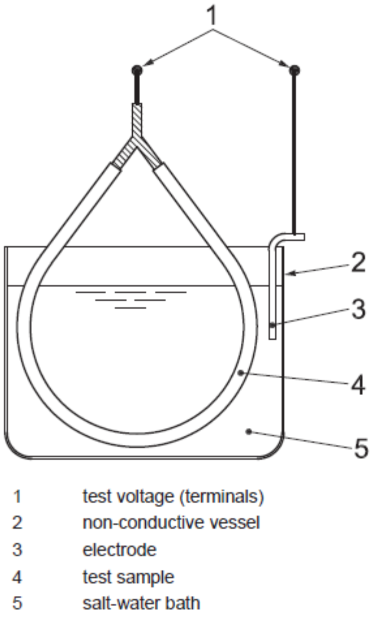

Figure 35. Test setup of the wire and insulation in the verification procedure. [8]

If the fire detector is in the form of a non-electric cable or hose, the verification procedure stated above does not apply. Instead several other test verifications may be of interest. As the most important factor for a fire detector that consists of a pressurised plastic hose is that no pressure equalization may occur, simple visual inspections are the most appropriate. However, if no visual alteration is noticeable, the material might still have been worsened by the ageing procedure which can lead to fatigue failure later on. A way of testing the mechanical characteristics of the polymer in this case may be in form of solid mechanics tests, such as stress and strain tests.

Long term heat ageing test

This test is intended to verify the upper value of the temperature endurance for the fire detector. The test is conducted by preparing two test specimens, either cable insulation or a plastic hose, each of a minimum length of 350 mm. An appropriate ageing temperature to be used is often mathematically estimated by using the Arrhenius equation. As the average operating temperature, T_{OP}, in engine compartments of heavy duty vehicles is somewhere between 80 to 130 °C in reality, a reasonable ageing temperature, T_{AGE}, could be 110 to 160 °C in order for the test to simulate about 8 years, which could be a typical service life of a bus, in 1000-1500 hours. This is an experience based estimation from experts in the field.

The test specimens are then wrapped around a mandrel as seen in Figure 36. The test samples shall be separated by at least 20 mm from each other and from the inner surface of the oven. Specimens made of different materials should not be tested simultaneously. After the ageing process, the test specimens should be withdrawn from the oven and maintained at standard atmospheric conditions for at least 16 h. After temperature stability has been reached, the specimen should be subjected to the *Low temperature winding test*, see below, followed by the *verification procedure*, see previous section. [8]

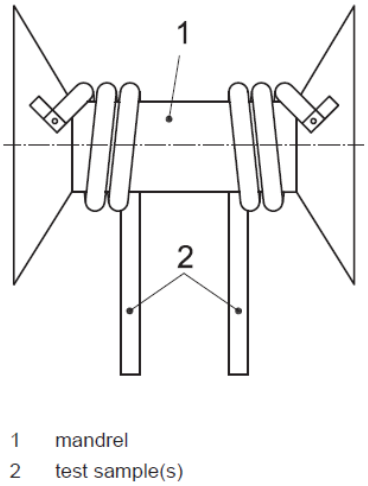

Figure 36. An illustration of the winding of the specimen around the mandrel. [8]

Low temperature winding test

This test intends to examine if the cable insulation or plastic hose can withstand bending at low temperature without cracking and still maintain intact, i.e. a cable should still have its insulation properties and a pressurised plastic hose should not have any leakage cracks that can stabilise the pressure inside. The test is therefore also used to detect defects caused by environmental stresses.

Two test specimens, either cable insulation or a plastic hose, of minimum length of 600 mm are wrapped around a mandrel for 0.5 to 3 turns, depending on its thickness, as seen in Figure 36. The mandrel and specimens should be placed in the test chamber at a temperature of -40 ± 2 °C where they must lie for a minimum of 4 hours. After the duration, the specimens are allowed to return to room temperature followed by a visual inspection for cracks and hollows. The *verification procedure*, see above, should follow. [8]

3.3 Heat

Heat can be defined as

$$Q = mc\Delta T$$

where m denotes the mass of the system, c is the specific heat capacity of the material and ΔT is the change in temperature for the body.

3.3.1 Heat transfer

A system always strives to reach a thermodynamic equilibrium according to the laws of thermodynamics. The way this is established is by heat transfer with the system's surroundings. Heat transfer can in general occur in three ways: conduction, convection or radiation.

Conduction refers to the transfer of internal energy on a microscopic level within a body. This can happen between two components, e.g. a bolt and a nut, which can be seen as a whole body when connected to one another. If the fire detector was to be placed so that it physically comes in contact with the engine block's hot side it would be heated by the conduction process occurring between the materials that are interconnected. The equation for a conduction process is governed by Fourier's Law as

$$q = \frac{\lambda A}{b}\Delta T$$

where q is the heat transferred (i.e. heat Q per second), λ is the thermal conductivity of the material, A is the heat transfer area, b is the material thickness, and ΔT is the temperature difference across the material.

Convection is the heat transfer process between fluids or gases and solids heated by the fluids or gases. The hot air inside the engine compartment heats the fire detector, thereby exposing the fire detector to a convective heat transfer process. The basic equation for a natural convection process is given by

$$q = h_{\mathrm{c}}\, A\, \Delta T$$

where q is the heat transferred, A is the heat transfer area of the surface, h_{c} is the convective heat transfer coefficient of the process and ΔT is the temperature difference between the fluid or gas and the surface. In case of forced convection the equation need to be modified.

Thermal radiation is the electromagnetic radiation that a body emits due to its temperature being above absolute zero (-273.15 °C), i.e. all bodies within the engine room will emit thermal radiation to other components all the time. Radiation is a method of heat transfer that does not rely upon any contact between the heat source and the heated object unlike the case with conduction and convection. Therefore, if the fire detector is placed near a hot surface, this surface will radiate heat and the expectancy of the total temperature within the fire detectors proximity may be misjudged. The Stefan-Boltzmann Law yields the equation for a radiation heat transfer process as

$$q = \sigma A T^4$$

where q is the heat radiated, A is the area of the emitting body, T is the temperature in Kelvin and σ is the Stefan-Boltzmann constant. [9, 10, 11]

3.3.2 Thermal loading

The term thermal loading is used to describe materials that are subjected to variations in temperature under certain loading conditions. Thermal loads can arise from both hot and cold sources, e.g. engines, fires, hot fluids or gases, cold ambient temperatures, low temperature fluids and so forth. Thermal effects on materials are an outcome of thermal loading and they do not only change the mechanical behaviour of materials, but also modify material properties, which can have critical consequences. As metals are heated to higher temperatures they can become more ductile which leads to larger deformations for the component under certain stress levels. The electrical resistivity of metals used in electrical circuits is increased with increased temperature which can cause electrical issues within the circuit. High temperatures can eventually lead to metals corroding that can result in sudden fatigue failure. As metals are heated they tend to expand, which causes volumetric issues inside the engine compartment. If metals are subjected to low temperatures during cold winter days for instance, they will become more brittle, thereby losing a lot of flexibility which can be hazardous in certain situations. Polymers are degraded if subjected to high temperatures for longer periods of time due to the ageing phenomenon explained in chapter 3.2. They also become softer and can even melt depending on how high the temperature is. If the ambient temperature in the surrounding is low however, polymers tend to be stiff which can lead to unwanted material behaviour at certain positions in the compartment. [12]

3.3.3 Suitable test method

In order to maintain a solid working environment for components in the engine compartment with regard to the possible variations in temperature, precaution must be taken in how to manage different heat scenarios during normal and deviating loading conditions for the vehicle. In order for components to withstand high or low temperatures without having their material characteristics altered with, tests need to be made where the component is subjected to temperature variations. The tests ensure that materials inside the engine compartment can survive the different temperature scenarios without having their material properties modified. A suitable standard to use is ISO 16750-4 [5], see below.

3.3.3.1 ISO 16750-4

There are six different temperature tests that can be performed, which have different impact on the component. The different tests are described in the following sections.

Dry heat test

This test simulates the exposure of e.g. fire detectors to high temperatures while being under electrical operation and control. The test is relevant in order to simulate the working environment in the engine compartment as temperatures can be very high. It is recommended that the relative humidity should not exceed 50% during the test.

The test is conducted by placing the test specimen inside the test chamber. Thereafter, the temperature inside the chamber is gradually increased so as to cause no harmful effects on the detector due to the temperature change. The gradual increase depends on the type of device that is being tested. The temperature is increased until the desired maximum temperature has been reached. Once done, the fire detector is powered on, the test commences and the detector is subjected to this maximum temperature for a duration of time. Suitable test conditions could be 110 to 150 °C for a duration of approximately 100 hours. After the duration has surpassed, the temperature is gradually lowered again in the same manner as it was increased until the temperature is the same as the ambient temperature outside the test chamber. [5, 13]

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes caused by the high ambient temperature inside the test chamber can be mechanical fracture, melting or deformation of materials (polymers in particular), loss of surface finish and optical properties due to overheating and internal short circuit due to the breakdown of electrical insulation materials.

Damp heat test

This test simulates the use of e.g. fire detectors under high ambient humidity while being switched on during normal operation. This test was created to resemble certain environments with high humidity, such as sudden rain during hot summer days or the working environment in rain forests where forestry machines operate.

The test starts by placing the fire detector inside the test chamber, both of which are at standard atmospheric conditions. The temperature should then be adjusted to the prescribed test condition and the detector should be allowed to reach temperature stability. This is accomplished by changing the temperature 1 °C every five minutes. During this period, and during the whole test, condensation on the fire detector must not occur. Once the temperature has been reached, the relative humidity should be adjusted to the corresponding test condition. This should be reached within two hours. Now the test is ready to commence for the chosen test duration. Suitable test conditions could be 40 °C at 93% relative humidity for a duration of 21 days. [14]

After the test duration, the equipment is shut off and the ambient conditions inside the test chamber are allowed to return to their normal values naturally. The specimen should be visually, electrically and mechanically inspected post testing. Typical failure modes are swelling of material, corrosion, discoloration, electrical malfunction caused by moisture, e.g. leakage current caused by a printed circuit board which is soaked with moisture.

Cold test

This test simulates the exposure of the fire detector to low temperatures while being powered on, e.g. the use of the detector at very low ambient temperature. This is the case for extremely cold operating environments for vehicles, such as for trucks being driven in Alaska for instance.

The fire detector is introduced into the test chamber which is at the same temperature as the surroundings. The temperature is then adjusted to the temperature appropriate to the degree of severity. Suitable test conditions may be -40 °C for a duration of 24 hours. The change in temperature should be 1 °C every five minutes. After temperature stability of the fire detector has been reached, it is powered on and then exposed to these conditions for the whole test duration. When the duration has elapsed, the temperature inside the chamber is then gradually heated at the same temperature change rate as it was cooled with until it has reached standard atmospheric conditions. [15]

The specimen should be visually, electrically and mechanically inspected post testing. Failure modes are mechanical fractures of materials, seal leakage due to loss of elasticity at low temperatures and electrical malfunction caused by low temperature.

Rapid change of temperature test

This is an accelerated test which simulates a very high number of slow temperature cycles in the engine compartment. The acceleration is possible due to a much higher temperature change rate and a bigger temperature change in one cycle in comparison to real vehicle stress. Because this test creates mechanical defects, such as cracks in the material, it is not required to have the test specimen powered on. The testing procedure can be seen in Figure 37.

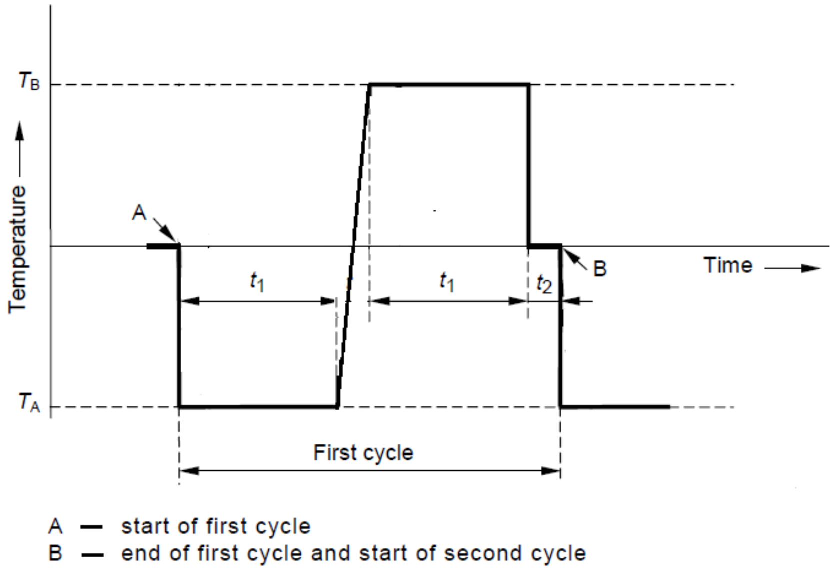

Figure 37. Illustration showcasing the temperature cycles. [16]

The test cycle starts by placing the detector inside the test chamber, starting at standard atmospheric conditions. The temperature inside the chamber should then be lowered to a cold temperature, T_A, as chosen in the *Cold test* within 15 seconds or less. This temperature should then be held for a specified period of time, t_1, preferably 180 minutes. After this duration, the specimen is exposed to a rise in temperature as to reach the hot temperature, T_B, as chosen in the *Dry heat test*. This temperature should be reached within 30 seconds or less. This temperature is once again held for the same duration, t_1. The temperature is finally decreased to the ambient temperature within 15 seconds, thereby concluding one rapid temperature change cycle. The recommended number of cycles for this test could be up to 1000. After the final test cycle, the detector should remain in standard atmospheric conditions until temperature stabilization has been reached, denoted by t_2 in the figure above. [16]

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes for this test are cracking of materials and seal failures due to ageing (polymers in particular) and different temperature expansion coefficients.

Hot air and cold water shock test

This test simulates the effects of thermal loading due to thermal shocks that are induced by cold water while the fire detector is in operation. The test applies to products in the splash areas of the vehicle. The purpose of this test is to simulate cold water splashing over a hot device. This happens when driving on wet roads during the winter or if the engine compartment is exposed to cold water whilst the temperature in the compartment is still high, e.g. if the engine room were to be cleaned with a high-pressure water jet right after the vehicle is powered off. The testing procedure is as follows:

- Place the test specimen, while in full operational mode, in a hot air oven at a temperature preferably between 110 to 150 °C for at least 60 minutes or until temperature stabilization has been reached.

- With the device still operating, submerge it for 5 min in an ice water tank, in a depth of more than or equal to 10 mm. The test fluid in the water tank should be de-ionised water between 0 to 4 °C.
- The time it takes for the detector to be transferred from the hot oven to the water tank should be less than 20 seconds.
- Minimum number of test cycles to be performed is 10.

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes in this test are mechanical cracking of materials, seal failures caused by different temperature expansion coefficients and loss of tightness. [5]

Cold and boiling water shock test
This test is similar to the *Hot air and cold water shock test* as it also simulates the effects of thermal loading due to thermal shocks. However, the difference is that in this test, the effects induced by boiling water are studied instead, rather than the effects of cold water.

In this test there are two baths, one containing cold water at 0 to 4 °C and the other containing hot or boiling water at 95 ± 5 °C. First off, the test specimen is placed in the cold bath and should be completely immersed by the fluid. It should be exposed to this condition for a duration of preferably 180 minutes. When the exposure period has elapsed, the detector is transferred to the hot bath within 20 seconds. Here it should lie for the same duration as in the cold bath. This is one test cycle and it should be repeated for a minimum of 10 times. At the end of the final cycle, the fire detector should be allowed to reach temperature stabilization in standard atmospheric conditions. [5]

The fire detector should be visually, electrically and mechanically inspected post testing. Failure modes in this test are similar to those in the *Hot air and cold water shock test*, i.e. mechanical cracking of materials, seal failures caused by different temperature expansion coefficients and loss of tightness.

3.4 Vibrations and shocks

Vibrational motions of mechanical devices, such as engines, that are in operation are typically unwanted. These motions can be created by imbalances in the rotating parts, uneven friction, the meshing of gear teeth and so on. Vibrations also generate forces that stretch, compress or twist the object or nearby components. This results in them experiencing alternating stresses and thereby stress-induced fatigue. The component's ability to handle these stresses depends on the magnitude and the number of alternating stress cycles. As a result, the component may eventually fail. [17]

Vehicles are frequently subjected to mechanical shocks in the course of their lifetime. These shocks can be a result of harsh bumps in the road during transportation, faulty layout design, hard braking etc. Although shocks have a short duration, mostly in the millisecond span, they are often severe and cannot be neglected. Therefore, the study of mechanical shocks is of vital importance as they cause critical damage on components if not managed properly. Unlike vibration, mechanical shock is a non-periodic force disturbance on an object characterised by suddenness and severity of a large force being reached in fractions of a second. Nevertheless, there are many similarities between the two when it comes to the generation of physical phenomena as well as the behaviour in the oscillations that occur. Therefore, the characteristic equations used to describe vibrations are also valid for shocks. Furthermore, while vibrations induce alternating stresses, shocks induce transitory dynamic stresses. While vibrations cause stress-induced fatigue failure, shocks can cause sudden fractures or plastic deformations that can have critical influences on surrounding components and the component itself. If the component does not fail instantly due to the experienced shock, it might fail later on due to accelerated fatigue because of the deformed shape of the component, thereby reducing its operational reliability. The shock induced stresses are a function of the shock's characteristics, such as amplitude, shape and duration, and the dynamic properties of the object exposed to the shock, such as resonant frequencies. [18]

3.4.1 Vibrations

Consider a vibratory system with a spring and a mass, see Figure 38.

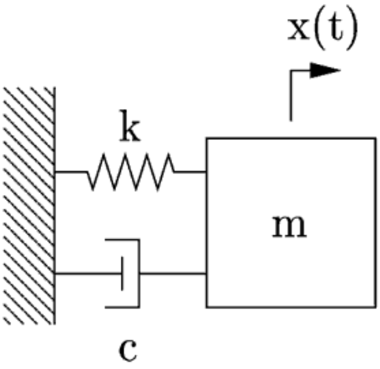

Figure 38. An illustration of a spring-mass system where k is the spring constant, c is the damping constant and x(t) is the displacement of the body with respect to time. [17]

The spring stores the potential energy while the mass, or the inertia, stores the kinetic energy of the oscillatory motion. The spring can be of any kind of elastic element, such as a beam, rotor, blade etc. If the vibrating spring-mass system is now disturbed from its stable position, the oscillations over a certain period of time will diminish. Thus, the system has a damper that absorbs energy from the vibrations and stops the oscillating motion completely. The damper can be a result of friction between components, a dashpot or even the vibrating component itself that undergoes alternating deformations during the vibrating occurrence. Therefore, in order to sustain the vibration, a disturbing force that continuously supplies the system with energy must be applied. If the system has significant damping, the vibration is called damped-forced vibration. If the damping is negligible, the vibration can be seen as undamped-forced vibration or undamped-free vibration, depending on if there is a continuous disturbing force acting on the system or not. When it comes to vehicles and vibrations, as long as the vehicle is in operation there will constantly be damped-forced vibrations acting on it. Regardless of if the vibrations are a result of the engine running while the vehicle is standing still or if they are induced by friction between the tires and the road while driving, there will always be a disturbing force acting on the vehicle. Therefore, only damped-forced vibrations will be considered further on. [17]

Consider an object that can be described as the spring-mass system shown in Figure 38 above. Assuming linearity and that the system has a single degree-of-freedom, the equation of motion when an oscillating force $F = F_0 \sin \omega t$ is applied on the system is then

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \omega t$$

where $m\ddot{x}$ is the inertial force of the object, $c\dot{x}$ is the damping force of the object and kx is the spring force of the object.

The steady state solution is

$$x = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + (c\omega)^2}} \sin(\omega t - \varphi)$$

The term φ is the phase lag of the displacement relative to the velocity of the object. When the angular frequency $\omega = \sqrt{k/m}$ it is often referred to as the natural frequency and is denoted ω_n.

The ratio of the amplitude of the steady-state response to the static deflection under the action of force F_0 is known as the magnification factor (MF). This is given by

$$\mathrm{MF} = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}}$$

where $\zeta = c/2\sqrt{km}$ is the damping ratio. When the damping ratio increases, the maximum value of the magnification factor decreases and vice-versa. When there is no damping ($\zeta = 0$), the MF reaches infinity at $\omega/\omega_n = 1$, i.e. when the frequency of the forced vibrations is equal to the frequency of the free vibration. This condition is known as resonance and can be catastrophic to structures or objects, as low frequencies are magnified indefinitely until the system cannot handle the vibrations and the induced stresses which results in total failure or collapse of the system. Note that if the damping is small and the frequency is close to the natural frequency, the issue of resonance can still arise as the MF will increase and amplify the vibrations in large proportions, thus causing complications to the structure. This can be of concern for components mounted in vehicles. [19]

However, in reality there are often much more complicated systems. As the tires of a vehicle are exposed to mechanical vibrations and shocks, by hitting a road bump for instance, these are transferred to mounted components inside the engine room through the suspension and frame of the vehicle. A vehicle therefore forms a complicated oscillatory system consisting of several damped multi-degree-of-freedom systems, see Figure 39.

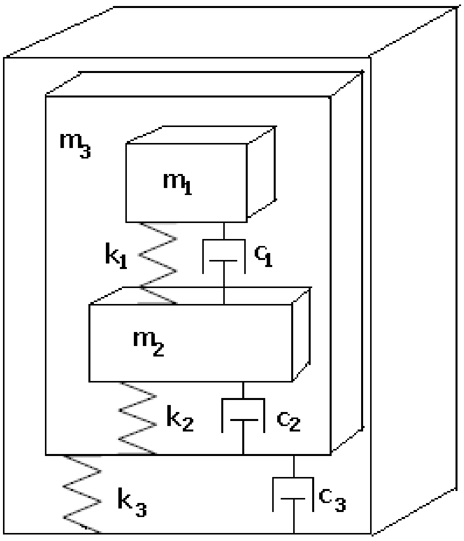

Figure 39. Example of a multi-degree-of-freedom system. [17]

3.4.2 Mechanical shocks

In reality, a shock does not have a simple pulse shape, as the component will dampen the shock out and the real shape of the incoming shock will have an oscillatory motion. Still, the part of the shock which is harmful for the component is the peak pulse of the whole oscillatory motion and it is this peak pulse that is represented by one of three common shock response pulse shapes. These pulse shapes are used as standards for analysis of components in the automotive industry, namely half-sine pulse, final-peak saw-tooth pulse and trapezoidal pulse. Each pulse filters the shock response differently. The half-sine pulse is the simplest type and diminishes most of the damping response. The trapezoidal pulse has a larger spectrum than the half-sine pulse and therefore yields more information about the damping response, see Figure 40. [20]

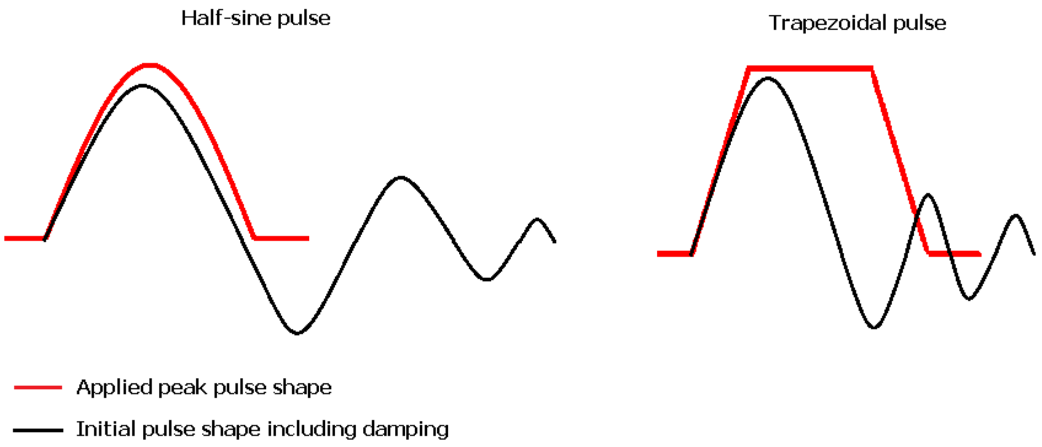

Figure 40. Difference between a half-sine pulse and a trapezoidal pulse and the response from the system (black graphs). [2]

When the component is subjected to a shock, the shock duration and peak acceleration of the component, i.e. the duration and the amplitude of the pulse shape, are observed. The peak acceleration is often measured in g-forces. Depending on which type of pulse shape that is applied, the velocity change of the component will vary. It is the sudden change in velocity of a component that is of interest when studying shock disturbances as only certain velocity changes are within an acceptable durability span. However, since the velocity change is indirectly dependent on the peak acceleration, the durability requirements are often given in terms of allowed g-forces. If the change in velocity is extremely high, the component will most likely be susceptible to some degree of mechanical alteration due to the shock-induced stress and later on it might completely fail. [18, 20]

3.4.3 Suitable test method

The most reasonable vibration scenario in engine rooms and vehicles is random vibrations, as the vehicle is subjected to continuous irregular oscillatory motions due to uneven roads and from the rotating machinery inside the engine room in reality. Random vibrations may be used to identify accumulated stress effects and the resulting mechanical weakness and degradation in the specified performance of the fire detector. The detector is mechanically connected to the mounting surface of the test apparatus either directly or through a rigid test fixture. The test apparatus is an electrodynamic or a servo-hydraulic vibration generator that generates random vibrations but it can also be stimulated to cause singular motions to simulate shock behaviour. Any connections to the specimen such as cables, pipes, bolts etc. should be arranged in a way that they impose similar restraint and mass as when the device is installed in its operational position. In order to achieve this, it may be necessary to fasten the additional connections to the fixture. The fundamental purpose of the test fixture is to transmit the mechanical influences from the test apparatus to the device. [21]

Most vibration and shock tests are performed under temperature influences. This is done in order to make the test resemble reality as much as possible. As components that are mounted in engine compartments of vehicles are subjected to both vibrations and temperature variations simultaneously while in operation, it is common for vibration tests to be performed under thermal cycling conditions as well. By doing so, both thermal and mechanical stresses will act on the device and the repercussions of these influences can be studied after the test. An example of a common failure is that a plastic part of a system mellows due to the high temperature and cannot withstand the vibration under this condition. The rapid temperature changes can occur due to sudden weather changes or if the engine load is increased. Therefore, it is practical to have the vibration apparatus inside a chamber that can change the temperature, a sauna-like test chamber for instance. The temperature intervals should be agreed upon between manufacturer and supplier but recommended values are the same maximum and minimum temperatures as in the *Dry heat test* and *Cold test* described in section 3.3.3.1. The cycle starts at the ambient temperature and is gradually cooled (about 4 °C/min) to the lowest permissible temperature where it is held for a period of 80 min. It is then heated with the same change in temperature as it was cooled with until the highest temperature has been reached. The maximum temperature is held for a duration as long as when the temperature was the lowest. Following this, the temperature is naturally cooled by heat transfer with the surroundings to the ambient temperature and a full temperature cycle has been completed. The temperature cycling is active continuously until the full vibration test has been concluded. It should be noted though that temperature cycling during vibratory tests is optional and should be agreed upon between manufacturer and supplier. [5, 21, 22]

3.4.3.1 **ISO 16750-3, IEC 60068-2-64**

The random vibration tests are carried out in order to investigate how rough driving influences the sprung mass of the vehicle. As the engine compartment is part of the sprung mass, i.e. the vehicle body, this is the most appropriate test to be made. The main failure to be identified by this test is breakage due to fatigue. The test is conducted by selecting the appropriate test frequency range f_{range}, the overall root mean square value of acceleration, G_{RMS} (see equation below), the shape of the acceleration spectral density curve (ASD) and the test duration. Usually, the test is carried out with a varying frequency range from 10 to 2000 Hz for a minimum of 8 hours (recommended about 60 hours) in each direction. The ASD is the usual way to specify random vibration. The spectrum decomposes the content of the random signal generated by the vibration into the different frequencies present in that process and helps identify periodicities. ASD is expressed in g^2/Hz (g is the gravitational acceleration) and is the relation between the acceleration of the test fixture at a specific frequency. G_{RMS} is the square root of the area under the ASD curve in the frequency domain and is calculated by

$$G_{\mathrm{RMS}} = \sqrt{\mathrm{ASD}(f_2 - f_1)}$$

G_{RMS} should be held constant during the test. Suitable values for ASD are 0.1-0.5 g^2/Hz. The specimen should be in full operational mode during the test and should be submitted to visual, dimensional and functional checks post testing. [21, 22]

3.4.3.2 **ISO 16750-3, IEC 60068-2-27**

Testing mechanical shocks is relatively straight forward and similar to how random vibrations are tested. The same test equipment is used in both cases and the test is conducted in the same directions as for vibrations. The only difference is that the test specimen is not subjected to the shock during long periods of time but instead to a number of shocks that last a certain amount of time and are in a certain g-force range. This test checks the specimen for malfunctions and breakage caused by shocks to the body and frame of the vehicle. The test simulates a load on the vehicle that occurs when driving over a curb stone at high speed for instance. Failure mode is mechanical damage, e.g. a detached capacitor inside the housing of the electronic device due to the occurring high accelerations or other critical failure. The specimen should be in full operational mode during the test and should be submitted to visual, dimensional and functional checks post testing. Example of recommended test conditions are half-sine pulse for a duration of 6 ms and peak acceleration of 10-20 g. The pulse is applied 10 times in each direction. However, it is also recommended that an additional test with about 50 g peak acceleration is performed once in each direction to verify the ability to withstand a small crash, since post-crash fires are common. [20, 22]

3.5 Electromagnetic compatibility

Electrical fields are created by the voltage difference between components or circuits and magnetic fields are generated by the current flowing through the electrical circuit when it is powered. Therefore in electronics the term electromagnetic field (EMF) is often used. The electromagnetic field affects the behaviour of charged objects in its vicinity in different ways. Most fire detectors are electronically operated and they transmit active feedback to an electrical control centre somewhere in the vehicle. Therefore, these types of detectors are classified as electronic devices.

In what way EMFs affect different components varies widely from case to case. By placing many electrical systems into a cramped space problems with electromagnetic interference (EMI) arise. The EMI between these systems occurs through radiated and conducted electromagnetic emissions, sometimes referred to as *crosstalk*. If the crosstalk is not controlled in a manageable fashion, it can cause many systems and other systems in their proximity to malfunction or fail completely. The electronics inside a vehicle are affected by both internal and external EMI sources. Internal EMI sources are simply the electrical systems that are installed in the vehicle, e.g. ignition system, fuel control system, cruise control, console applications etc. In short, these systems give rise to EMI due to the electrical circuits inside the vehicle emitting EMFs of different strengths. Sometimes EMI problems show themselves as noise on the radio, which is not harmful for the functionality of the vehicle but can be of nuisance. In some cases on the other hand, the crosstalk can be dangerous as it can cause loss of control of the vehicle. Therefore, it is essential to design “mission critical” systems that can deal with the safety and control of the vehicle to withstand the impact of certain EMI sources and sizes. External EMI sources include Bluetooth devices, cell phones, third-party navigation, high power transmitters such as radio towers etc. Since the impact of these sources is uncontrollable due to the EMI amount varying irregularly, it is important to design EMI shielding, grounding and filtering properly, often in a way that critical systems can tolerate the worst case scenario. However, EMIs are not the only sources of interference for electronics. Another common interference is voltage deviation within the electrical circuit. This interference is caused by conducted transient disturbances from electrical/electronic sub-assemblies (ESA) to the power supply line or by the power supply line to ESAs. An ESA is an electrical device that is part of an interconnected electrical system consisting of many electrical devices, as is the case for a fire detector. Electrical disturbances can often cause false alarms in different electrical systems or simply lead to certain systems not activating at all, which can lead to critical vehicle failure in the end. Another aspect that is common within this area is a phenomenon called electrostatic discharge (ESD). ESD is caused by a sudden discharge between two objects that come in contact with one another and that have different electrical charges. The discharge erupts in the form of a microscopic spark which can burn through the electrical circuit in the device. Since ESAs in engine compartments are interacted with physically on a regular basis, either by mechanics' hands or tools during vehicle maintenance or by environmental impacts such as the surrounding air, ESD control is of high importance as it can cause sudden failures to devices. [23]

Due to the progression in the automotive industry and the advancement of technology in recent years, more and more electrical systems and devices are fitted in vehicles. In order for these systems to function correctly even though EMFs and EMIs are continuously present, these influences need to be managed in some way. Electromagnetic compatibility (EMC) is one way to control EMIs from different systems and devices so that unwanted effects are prevented. Since all vehicles differ when it comes to handling EMIs due to irregular amounts or different types of electronic systems fitted, current standards that ensure certain ranges of permissible EMIs or electrical disturbance exposure are often applied. In some cases, standards are required by law and sometimes current standards are tweaked with manufacturer specific requirements.

3.5.1 Suitable test method

EMC tests on certain electrical devices can be conducted in two ways. One of them is by testing their electromagnetic compatibility whilst mounted in the vehicle. By doing so, the test assures that the device, i.e. the fire detector, is compatible with the electromagnetic environment for that specific engine compartment. By changing the environment, meaning installing the same detector in the engine room of another vehicle type, it can result in improper functioning due to the composition of installed electronic devices being different and therefore indirectly affecting the detector negatively. Consequently, the detector will need different manufacturer specific EMC requirements in this environment than in the previous one. The alternative way of testing the fire detector is by conducting "isolated" tests. The detector is then removed from the engine compartment and tested in a facility where it should withstand certain EMC requirements. Recommended "isolated" tests prior to mounting in the vehicle are tests according to the United Nations regulation: UNECE Reg. 10 [24], as it assures that it will tolerate the harshest EMC requirements regardless of the environment it is mounted in. If a fire detector has been tested this way and is to be mounted in the engine compartment of a vehicle, it is most likely that if further requirements are determined, they are manufacturer specific and serve only as a complement to the requirements made by the UN regulation. This is usually the case if the manufacturer wants to be certain that the detector will not disturb other important electrical equipment mounted in that specific engine compartment and vice versa.

3.5.1.1 **UNECE Regulation 10**

Below is presented the different types of tests included in UNECE Regulation 10.

Narrow and broadband EMI generated by ESAs

This test is intended to measure narrow- and broadband electromagnetic interferences generated by ESAs, i.e. investigate the EMI strength (dB µV/m) that the fire detector will emit while powered on. The fire detector shall be in normal operation mode during the test, preferably on maximum load. The limits apply throughout the frequency range 30 to 1000 MHz for measurements performed in a semi anechoic chamber with a spectrum analyser or a scanning receiver. [24]

Immunity of ESAs to electromagnetic radiation (EMR)

When testing the immunity of ESAs to EMR there are many possible test methods to be used. A common method is by using an 800 mm stripline. This method can test complete electronic systems including sensors and actuators as well as the controller and wiring loom. It is suitable for ESAs whose largest dimension is less than one-third of the plate separation, which is often the case with fire detectors as they are relatively small. The fire detector is positioned centrally between two parallel metallic plates separated by 800 mm. It is then subjected to an electromagnetic field. The detector shall be switched on and stimulated to be in normal operation condition during the whole test. To ensure that reproducible measurement results are obtained when tests and measurements are repeated, the test signal generating equipment and its layout shall be the same each time the test is performed. The test will be performed with frequencies ranging between 20 to 2000 MHz. At each desired test frequency, a level of power is fed into the stripline to produce the required EMR field strength. The immunity test levels should be to a minimum of 30 V/m over the whole 20 to 2000 MHz frequency band. If the fire detector fails the test it should be verified as having failed under the relevant test conditions and not as a result of the generation of uncontrolled fields. [24]

ESAs’ immunity to transients disturbances and the emission of transients disturbances from ESAs

These test methods should ensure the immunity of ESAs to conducted transient disturbances on the vehicle power supply and limit conducted transient disturbances from ESAs to the vehicle power supply. The methods are only applicable if the vehicle power supply line is 12 or 24 V.

When testing the immunity of ESAs to transients, five different test pulses are applied to the supply line. These voltage pulses are generated by an external pulse generator coupled to the supply line. Each pulse simulates a different scenario and the test pulse generator should be capable of producing an open circuit test pulse for each situation. The test pulses are categorised as 1, 2a, 2b, 3a and 3b and are defined in Table 1.

Table 1. Description of the five voltage pulses that are supplied by the voltage generator.

Test pulse	Description
1	Simulates transients due to supply disconnection from inductive loads. It applies to an ESA if it remains connected directly in parallel with an inductive load.
2a	Simulates transients due to sudden interruption of currents in a device connected in parallel with the ESA due to the inductance of the wiring harness.
2b	Simulates transients from DC motors acting as generators after the ignition is switched off.
3a	Simulates transients that occur as a result of the switching processes. The characteristics of these transients are influenced by distributed capacitance and inductance of the wiring harness.
3b	

The test procedure to evaluate ESAs for conducted emissions of transients along supply lines of a device under test are performed as follows. The supply voltage and the disturbance voltage generated by the ESA shall be measured using a voltage probe and an oscilloscope. The test applies to an inductive load with a large inductance or a high load current, which connects to the vehicle power supply or an ESA which switches such an inductive load. If an inductive load has a small inductance or a low load current and is driven by an internal regulated voltage, e.g. 5 V, which is isolated from the vehicle power supply, the test is not applicable unless specified in the test. Two types of conducted emission transients are tested, namely slow and fast pulses. The sampling rates and trigger levels for the different test pulses should capture a waveform displaying the complete duration of the transient disturbance. By utilizing the proper sampling rate and trigger level, the voltage amplitude should be recorded by powering on the fire detector according to the test plan. Other transient parameters, such as rise time, fall time, transient duration etc. may also be recorded but are not necessary. Unless otherwise specified, ten waveform acquisitions are necessary. It is obligatory to report only the waveforms with the highest positive and negative voltage amplitude. [25]

ESD

There are two forms of ESD and they occur either by physical contact with the ESA or when the ESA is discharged due to the surrounding air. Therefore, simulated discharges can be applied by two discharge modes: contact and air. In contact discharge mode, the tip of the ESD generator's discharge electrode is brought in contact with the fire detector before the discharge switch is triggered to apply the discharge. An ESD generator is an instrument that simulates the human ESD model, i.e. a human charged with a higher level of static electricity than the fire detector. When air is the cause of the discharge, the discharge electrode is charged to the test voltage and then brought with the demanded speed of approach to the fire detector, applying the discharge through an arc that ensues when the tip approaches close enough to the ESA to break down the dielectric material between the tip and test point. The speed of approach of the discharge electrode is a critical factor in the rise time and amplitude of the injected current during an air discharge. The ESD generator should therefore in practice approach the fire detector as fast as possible until the discharge occurs or the discharge tip touches the discharge point without causing damage to the detector or the generator.

In reality ESD can be caused by both direct and indirect discharges. The direct type discharges, either by contact or air, are applied directly to the detector and to the remote parts that are accessible by the vehicle user, e.g. switches and buttons. This also applies on physical contact between persons and the fire detector or external objects and the detector. The indirect type discharges happens due to contact with other conductive objects in the proximity of the fire detector and are applied through an intervening metal. The tests are done while the detector is powered on in normal operating mode and when it is delivered from supplier prior to mounting in the vehicle. [26]

Once the testing has been completed, the fire detector should pass complete function testing successfully. There shall be no permanent damage. In addition, the effectiveness of the EMC protective circuits e.g. input capacitors ensuring electromagnetic interference immunity and emission, respectively, should be tested after ESD exposure.

3.6 IP-classification

Engine rooms in vehicles are one of the harshest operating environments for electronics within the vehicle. Electronic equipment is often enclosed in a way that minimal penetration from mechanical impacts, dust, corrosion and corrosive substances, moisture or water occurs. These factors can often lead to short circuits in electronic devices and therefore risks of electric shocks, fires or explosions can be an issue. IP-classification, or International Protection Code (IP Code), IEC 60529, is a system used for classifying the degrees of protection provided by the enclosures of electrical equipment or electronic devices. This includes the following protection aspects: [27]

- Protection of individuals against access to hazardous parts inside the enclosure.
- Protection of the equipment inside the enclosure against ingress of solid foreign objects.

- Protection of the equipment inside the enclosure against harmful effects due to the ingress of water.

The degree of protection provided by an enclosure is indicated by the IP Code and is written in the form of: IPXxYy, the last two indices being optional. The indices are explained below:

- X – protection of *equipment* against ingress of solid foreign objects and protection of *persons* against access to hazardous parts, seen as a numeral between 0-6 or letter X (undetermined).
- x – protection of *equipment* against ingress of water with harmful effects, seen as a numeral between 0-9 or letter X (undetermined).
- Y – protection of *persons* against access to hazardous parts, i.e. a part that is hazardous to approach or touch, seen as letter A, B, C or D. This index is optional.
- y – supplementary information regarding the type of condition that is applied during the test, seen as letter H, M, S or W. This index is optional.

The first numeral indicates that the enclosure provides protection of people against access to hazardous parts by preventing or limiting the admittance of a part of the human body or an object held by a person. The enclosure must simultaneously provide protection of equipment against the ingress of solid foreign objects. Therefore, both conditions for a given first numeral in the IP Code with regard to equipment and individuals needs to be met.

The second numeral in the IP Code specifies the degree of protection provided by enclosures regarding harmful effects on the equipment due to the ingress of water. These tests are carried out with fresh water. The actual protection may not be satisfactory if other solvents are used or by exceeding the requirements regarding pressure and temperature. During the test, the moisture contained inside the enclosure may partly condense. The dew which may thus occur shall not be mistaken for ingress of water.

Up to and including IPX6, compliance with the requirements for all lower numerals is implied. The tests establishing compliance with any one of the lower degrees of protection than IPX6 therefore does not necessarily need to be carried out, provided that these tests obviously would be met if applied. Requirements that are met by IPX7-IPX9 do not need to comply with the requirements for IPX6 and lower. If compliance is a necessity, the IP Code must be multiple coded, e.g. IPX6/IPX9, which then indicates that all requirements are met regarding exposure to all types of water jets. If any water has entered during the inspection after the test, acceptance conditions are:

- The amount of water should not be sufficient enough to interfere with the correct operation of the equipment or impair the safety of people.
- The water shall not remain on insulation parts where it could lead to tracking along the creepage distances.
- The water must not reach live parts or windings not designed to operate when wet.
- The water may not accumulate near the cable ends or enter the cables, if there are any.
- The inspection should prove that any water that has entered does not accumulate at drain holes on the enclosure, if there are any, and that it drains away the water without harming the equipment.

The letter indices are only used if the actual protection against access to hazardous parts is higher than that indicated by the first numeral or if the first numeral is represented by an X. Supplementary information, represented by the letters H, M, S or W, conform with specific conditions that apply during the tests, if there are any. The absence of the letters S and M implies that the degree of protection does not depend on whether parts of the equipment are in motion or not. This may necessitate tests being done under both conditions. However, the test establishing compliance with one of these conditions is generally sufficient, provided that the test in the other condition obviously would be met if applied.

Table 2 below showcases a description of the IP Code indices. If the product does not have a specification for protection of equipment against ingress of water or solid objects, the numeral is replaced by the letter X and the IP Code is then written as e.g. IP3X with respect to ingress of solid objects (no info on ingress of water) and IPX3 with respect to ingress of water (no info on ingress of objects).

The first numeral indicates that the enclosure provides protection of people against access to hazardous parts by preventing or limiting the admittance of a part of the human body or an object held by a person. The enclosure must simultaneously provide protection of equipment against the ingress of solid foreign objects. Therefore, both conditions for a given first numeral in the IP Code with regard to equipment and individuals needs to be met.

The second numeral in the IP Code specifies the degree of protection provided by enclosures regarding harmful effects on the equipment due to the ingress of water. These tests are carried out with fresh water. The actual protection may not be satisfactory if other solvents are used or by exceeding the requirements regarding pressure and temperature. During the test, the moisture contained inside the enclosure may partly condense. The dew which may thus occur shall not be mistaken for ingress of water.

Up to and including IPX6, compliance with the requirements for all lower numerals is implied. The tests establishing compliance with any one of the lower degrees of protection than IPX6 therefore does not necessarily need to be carried out, provided that these tests obviously would be met if applied. Requirements that are met by IPX7-IPX9 do not need to comply with the requirements for IPX6 and lower. If compliance is a necessity, the IP Code must be multiple coded, e.g. IPX6/IPX9, which then indicates that all requirements are met regarding exposure to all types of water jets. If any water has entered during the inspection after the test, acceptance conditions are:

- The amount of water should not be sufficient enough to interfere with the correct operation of the equipment or impair the safety of people.
- The water shall not remain on insulation parts where it could lead to tracking along the creepage distances.
- The water must not reach live parts or windings not designed to operate when wet.
- The water may not accumulate near the cable ends or enter the cables, if there are any.
- The inspection should prove that any water that has entered does not accumulate at drain holes on the enclosure, if there are any, and that it drains away the water without harming the equipment.

The letter indices are only used if the actual protection against access to hazardous parts is higher than that indicated by the first numeral or if the first numeral is represented by an X. Supplementary information, represented by the letters H, M, S or W, conform with specific conditions that apply during the tests, if there are any. The absence of the letters S and M implies that the degree of protection does not depend on whether parts of the equipment are in motion or not. This may necessitate tests being done under both conditions. However, the test establishing compliance with one of these conditions is generally sufficient, provided that the test in the other condition obviously would be met if applied. [27]

Table 2. IP Code indices and description.

Numeral or letter	**Protection of *equipment***	**Protection of *persons***
First numeral	**Against ingress of solid foreign objects**	**Against access to hazardous parts with:**
0	Non-protected	Non-protected
1	Object ≥ 50 mm diameter	Back of hand
2	Object ≥ 12,5 mm diameter	Finger
3	Object ≥ 2,5 mm diameter	Tool
4	Object ≥ 1,0 mm diameter	Wire
5	Dust-protected	Wire
6	Dust-tight	Wire
Second numeral	**Against ingress of water with harmful effects**	
0	Non-protected	–
1	Vertically dripping	
2	Dripping (15° tilted)	
3	Spraying (Up to 60° from vertical)	
4	Splashing (Any direction)	
5	Jetting (2.5-3 m distance)	
6	Powerful jetting (2.5-3 m distance)	
7	Temporary immersion (30 min)	
8	Continuous immersion	
9	High pressure and high temperature water jet	
Additional letter		**Against access to hazardous parts with:**
A	–	Back of hand
B		Finger
C		Tool
D		Wire
Supplementary letter	**Supplementary information specific to:**	
H	High voltage apparatus	–
M	Motion during water test	
S	Stationary during water test	
W	Weather conditions	

4 Conclusions

The environmental conditions in the engine compartments of heavy duty 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 vary from 10 m^3, and almost cubic compartments with no components more than 1.5 m above the compartment floor, to 1 m^3, completely cluttered from floor to ceiling. The area around the engine is often similarly cluttered with the components situated quite tightly together, but the rest of the compartment could be both almost empty or fitted with extra equipment to manage other things than just the traction.

Ventilation and airflow is another subject which differs from vehicle to vehicle. Some are completely air tight and cooled by liquid only, while others are open and cooled by the forced air flow of a large fan. Normally the situation is somewhere in between.

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 duty vehicles manage the environmental conditions discussed above and standards are used to ensure that. Suitable standards and test methods are discussed in this report and some of them will be used in the new test method for fire detection systems. Which ones that will be used are decided later in this project (WP6). Now it can be concluded that some requirements, e.g. corrosion resistance, are easier to implement for all types of vehicles, while other environmental conditions, such as vibrations, could need different requirement levels for on-road vehicles and off-road vehicles.

Tests for temperature variations, ageing, corrosion, vibrations, shocks, and EMC will (if included in the test method, WP6) mean separate tests, while exposure of particles and different ventilation conditions in appropriate geometries will be included in the detector performance tests (fire tests).

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Appendix A: Photos of engine compartments

Figure 41 Engine compartment of a wheel loader, the warm side of the engine.

Figure 42 Engine compartment of a wheel loader, the cold side of the engine.

Figure 43 Engine compartment of a trommel screener.

Figure 44 The engine compartment of a star screener.

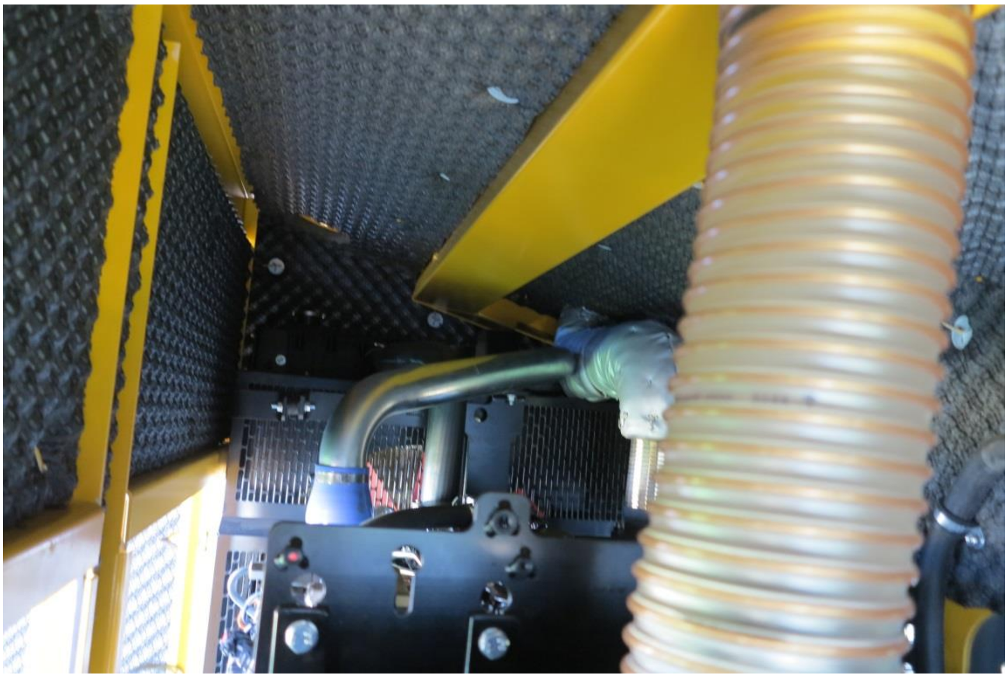

Figure 45 Open space in the upper part of the engine compartment in the star screener in Figure 44.

Figure 46 Engine compartment of a bus.

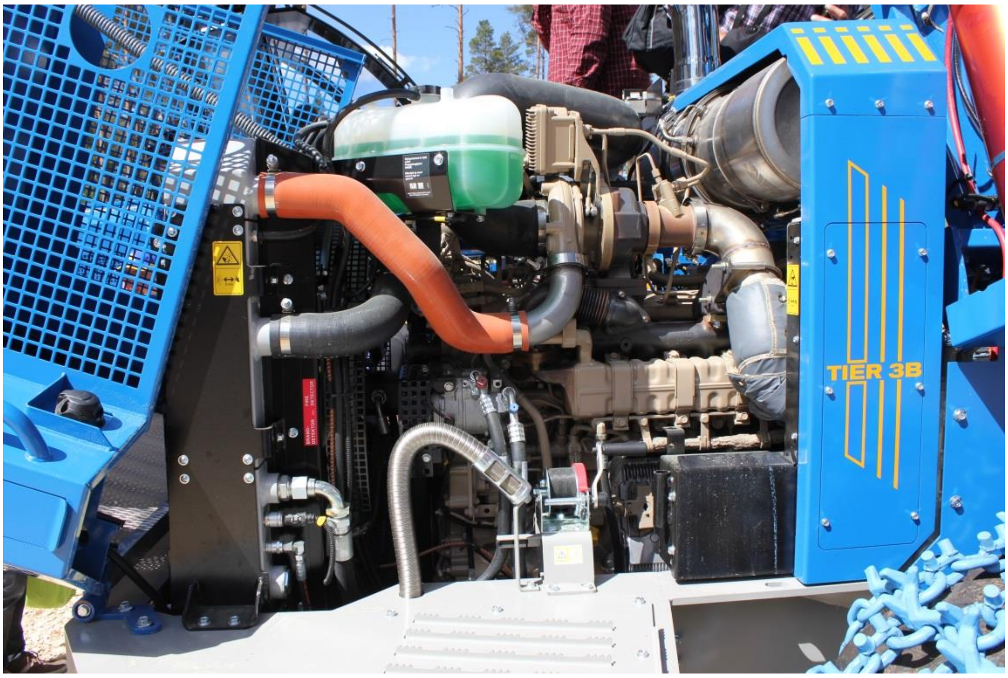

Figure 47 The warm side of the engine compartment in a forestry machine.

Figure 48 Engine compartment of a forestry machine.

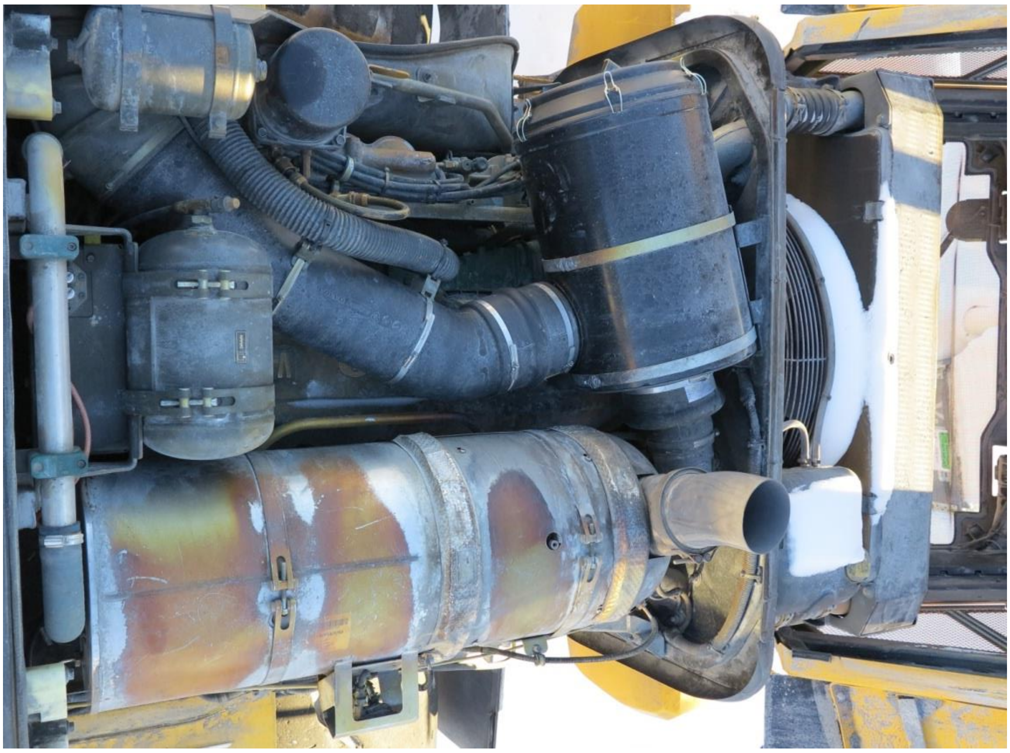

Figure 49 Engine compartment of a wheel loader. Cooling fan is situated in the right part of the picture in a different compartment than the engine.

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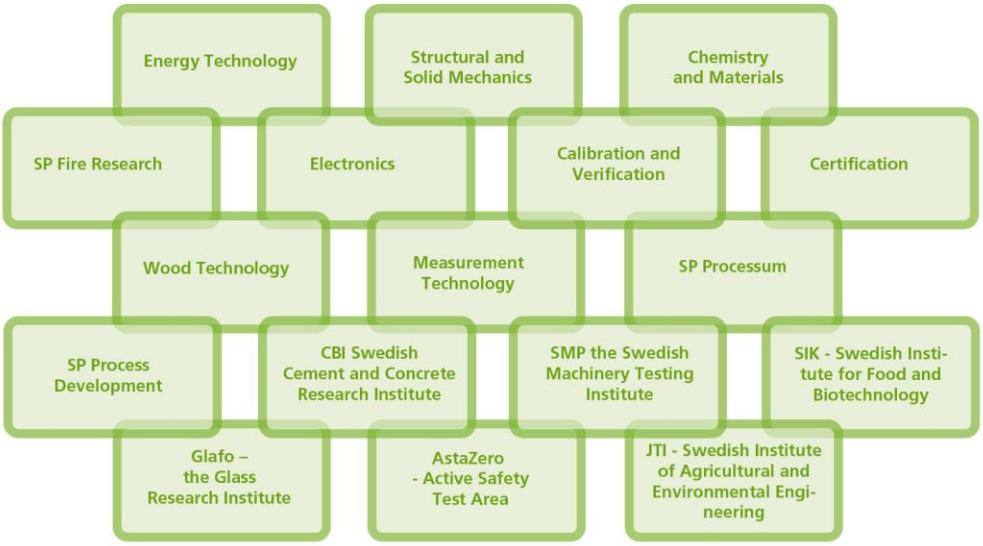

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