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Pre-ignition detection and early fire detection in mining vehicles

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ABSTRACT

With an increasing demand for early detection of mining vehicle fires, the question is how an early detection could be achieved? Data from cone calorimeter tests and incident summary data were applied when analysing possible fire detection solutions on mining vehicles. Based on the tests, pre-ignition and post-ignition solutions in the cab and the engine compartment were analysed and presented. If overcoming the challenges of the environment, smoke sensors could for example be a potential pre-ignition detector in engine compartments. Based on the incident summaries, clues on detectable traces, etc., were identified and a discussion on the types of sensors for various types of vehicles and sections was provided. Fires in for example the turbo/exhaust area and engine compartment, could be detected prior to ignition using gas sensors to detect the emitted hydrocarbons or an oil mist detection system.

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Pre-ignition; fire detection; mining vehicle; cone calorimeter; incident summary; smoke detection; underground mine; surface mine

Introduction

One of the key components regarding fire safety in the mining industry is an early detection of the occurring fire, increasing the likelihood of extinguishment and providing ample of time for evacuation. With deeper mines (i.e. longer distances) and fully or partially autonomous mines (with less miners present to detect fires and take action), the need for early detection will increase even further. Battery-powered mining vehicles will also increase the demand for early detection, increasing the likelihood of a successful extinguishment. Several studies on fires in the mining industry have shown that vehicles or mobile equipment is one of the dominant fire objects in the mining industry (De Rosa 2004; Hansen 2009, 2018), rendering the early detection of fires in mining vehicles of high interest.

Several earlier studies have been conducted on fire detection in the mining industry, but very few on mining vehicles or the provision of very early fire detection potentially prior to the ignition of the vehicle fire. The far majority of the earlier studies has been aimed at fire detection in mine sections involving burning coal, conveyor belt, wood, etc. Conti (1992) and Conti and Litton (1995) presented studies on the alarm times of different types of sensors to different types of simulated mine fires: a slowly burning coal and conveyor belt fire, a rapid flammable liquid and belt fire, and a flammable liquid and belt fire where diesel exhaust was present. It was found that smoke sensors would detect several minutes before carbon monoxide (CO) sensors, and that CO sensors would provide earlier warning than the point type heat sensor. Litton (2002) conducted experiments in order to develop design criteria for early and reliable fire detection in atmospheres that could be contaminated by products emitted from diesel engines. It was found that a combination of ion chamber and light scattering module provided excellent discrimination capabilities as a fire sensor for the detection of developing fires in atmospheres contaminated by diesel particulate matter. De Rosa and Litton (2010) performed a number of experiments in a cab like compartment – using a mixture of diesel and petrol as fuel – to evaluate optical flame detectors, photoelectric smoke detectors, and combined ionization and photoelectric smoke detectors for detecting mining equipment cab fires. It was found that an optical flame detector with a 180° field of view and a combined ionization and photoelectric smoke detector installed in the cab would provide an early detection, allowing the operator to take required actions and safely exit the cab. Perera and Litton (2011) presented a study on the properties of smoke particles produced from both flaming and non-flaming combustible materials (wood, coal, conveyor belt, battery cover and diesel) found in mines and how these properties influenced an early fire detection. Large differences were found between flaming and non-flaming smoke particles (size, morphology and radiative transfer properties). Based on the analyses, possible techniques for early fire detection and discriminating fire sensors in mines and tunnels were highlighted. Litton and Perera (2012) performed large-scale experiments in an above ground gallery, simulating typical flaming fires along conveyor belts with coal mass in underground

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coal mines. During the experiments, earlier developed fire detection criteria were validated for different types of fire-resistant conveyor belts, air velocities and cross-sectional areas. Yuan et al. (2018) conducted an experimental study on the responses of different sensors for early detection of diesel fuel fires in a storage area. During the experiments, the size of the fire, the ventilation velocity and fire location were varied. It was found that the flame sensor and the smoke sensors detected the fires earlier in most cases compared to the CO sensors.

This study was overtaken to investigate the existence of features or characteristics of the pre-ignition and early fire environment of mining vehicles, which could potentially be used as an input when designing the fire detection. When investigating features and characteristics of the pre-ignition and early fire environment, fire experiments – involving solid fuel items commonly found on mining vehicles – were conducted to investigate the emission of combustion products and heat. The effectiveness of the combustion products and heat was evaluated with respect to pre-ignition as well as early fire detection. A large number of incident summaries from the mining industry was used to analyse the detection of previously occurred fires in mining vehicles, giving clues on detectable traces, occurring faults, characteristics and development during pre-ignition and the early fire phase. Based on the findings from the experiments and summaries, a discussion on the types of sensors for various types of mining vehicles and vehicle sections is provided. When designing the fire detection of a mining vehicle, a more specific analysis will have to be performed. The results and discussion found in this paper should be regarded as a starting point, initiating a work which will increase the safety of mining personnel.

Pre-ignition, early fire behaviour and fire detection in mines

Pre-ignition, early fire behaviour and detectable traces

With a fuel source and an ignition source, the heating of the fuel source will commence. Given that the process will be dependent on continued external heating at the early stages and with oxygen present, a pyrolysis may initiate. Prior to the ignition of the fuel source, no flames will be present. The emitted pyrolysis products – but also early emitted combustion products following upon ignition – may have a laminar type of flow, which will be more difficult to visually discern compared with a more turbulent flow associated with an increasing fire intensity. Depending on the type of fuel source and the access to oxygen, the emitted pyrolysis products will vary.

Pre-ignition will in the case of flammable or combustible liquids imply the vapourization of the liquid or the emission of a liquid spray (the latter resulting in a spray fire upon ignition). Traces in these cases will be the vapours and sprays emitted.

Following upon the ignition of the fire, the incipient phase of a fire is distinguished by a fire positioned at the site of origin, gradually getting less dependent of the ignition source – if not being extinguished – but still sensitive to random fluctuations in the immediate environment. The fire development during the incipient phase may follow a rapid growth with flaming combustion or a slow growth with smouldering combustion. Influencing parameters include the heat release rate of ignition source, position of ignition source, type of fuel, fuel distribution, constellation of fuel, smouldering or flaming combustion, interaction between the fire and any compartment boundaries and access to oxygen. The duration of the incipient phase may be very long during a smouldering combustion as opposed to a generally much shorter duration during flaming combustion due to higher spread rate caused by the radiative heat transfer from the flames. It is desirable to detect the fire prior to exiting the incipient phase as the fire subsequently will commence a growth phase with increasing fire intensity. Earlier studies have identified a threshold – when exiting the incipient phase – in the 20 to 50 kW range (Sundström 1995; Bukowski 1995; Ristić 2001; Buchanan 2001; Collier and Whiting 2008) or a flame height of approximately 0.25 m (Fitzgerald 2004).

When detecting fires we take advantage of the traces emitted by the fire: gas, smoke, flames and heat. Depending on the type of fuel, the porosity of the fuel, the ventilation conditions, etc., the earliest detectable trace of the post-ignition fire will vary. A flaming fire in a solid fuel will initially be detectable by the gas or the smoke followed by the flame and the heat. A smouldering fire in a solid will be detectable by the gas or the smoke but will not be detectable by any flame radiation. A fire in a flammable liquid may initially be detectable by the flame radiation before sufficient amount of smoke is emitted.

The types of gases and the amount of smoke emitted from a fire will depend on the type of fuel involved and the access to oxygen. Examples of types of gases could be CO, CO_2, H_2O, NO_x, HCl, H_2 and SO_2, with CO and CO_2 being the typically most common gases from fires.

Different fire detection sensors

The different types of sensors have different advantages and disadvantages depending on the type of conditions at the site and the fire behaviour. Applying more than one type of sensor will often provide a solution where the individual advantages of the sensor types leads to a faster detection, an extended detection capability and a robust detection solution.

Heat detection

Heat detection will take advantage of the heat emitted from the fire and is one of the common methods to detect fires in engine compartments. Heat detection can be achieved applying either point heat detectors or linear heat detectors.

Point heat detectors can be either a fixed temperature type or a rate-of-rise type, where the rate-of-rise heat detector is activated when the temperature increase per unit time exceeds a certain threshold. Due to its nature, the rate-of-rise heat detector may not activate during a slowly developing fire. The activation of a point heat detector during a fire in a compartment with a distinct ventilation flow may be delayed as the hot fire gases may be diluted and cooled down before reaching the detector. Thus, the positioning of point heat detectors with respect to the fire and ventilation flow is crucial. Point heat detectors have the advantage of being insensitive to environmental conditions typically found in the mining industry.

Linear heat detectors consist of entire lengths of cables, hoses or optical fibres, which constitute the sensor. The linear heat detectors have the advantage of an increased covering, which will increase the likelihood of an activation in a compartment with high temperatures and ventilation flow.

Hot surfaces or high ambient temperatures may cause false alarms from heat sensors.

Flame detection

Flame detection takes advantage of the electromagnetic radiation from the flames and will therefore not provide any pre-ignition detection. A free line of sight is crucial for the operability of the flame detector and any obstacle in the line of sight or obscuration on the lens will delay or even prevent the detection. The detector will also have to be fairly well aimed at the potential fire source, preventing delays in the detection. As opposed to heat detectors, flame detectors are not affected by the airflow to any great extent except regarding the tilting of flames. Potential causes of false alarms are hot objects and flashes of light, but technical solutions are available to eliminate the error sources. Flame detectors could for example be an option in engine compartments, aimed at detecting rapidly growing, flaming fires such as spray fires.

Smoke and gas detection

Smoke and gas detectors take advantage of the soot and gas substances emitted from the fire. Depending on the type of fuel and the access to oxygen, the type of gas substances and amount of soot emitted will vary.

Smoke and gas detectors are divided into point type and aspirating type detectors. The aspirating type of detector may be positioned outside a challenging environment and the air drawn through pipes from different positions in the compartment.

The advantage of smoke and gas detectors is the ability to detect fires during the incipient phase, smouldering fires and slowly growing fires as well.

The disadvantage of smoke and gas detectors is the sensitivity to harsh environmental conditions and the risk of false alarms. Potential false alarms for smoke detectors may include exhaust fumes, oil on a hot surface or glycol on a hot surface. Potential false alarms for gas detectors may include diesel vapour and exhaust fumes. Given the conditions in an engine compartment and the risk of false alarms, the use of smoke or gas detectors can pose a challenge. Nevertheless, if successfully implemented it would be of benefit, resulting in an early fire detection. A potential technology could be a so-called electronic nose (Charumporn et al. 2004). An electronic nose system consists of a number of different metal oxide gas sensors, capable of detecting the incipient or the early phase of various types of fire sources. When using multiple sensors, the ability to detect a number of different gases at various concentrations increases. The technology could for example be an option in engine compartments or cab compartments.

The mining and mining vehicle environment

The mining environment poses a true challenge to fire detection due to a number of influencing factors, which may cause false alarms, delayed or failed activations. Smoke particulates and carbon monoxide will be emitted from diesel equipment as well as welding or grinding activities, causing false alarms. The wear and tear in a mine and the risk of corrosion will negatively affect the operability of the fire detection system and its life cycle. The atmosphere underground may be very humid and with temperature changes the risk of corrosion will be ever present and may cause interference to the operability of the fire sensors.

The fire detection in engine compartments of mining vehicles will be a challenge given the conditions found in the compartments. An environment with objects with high surface temperatures, shocks, vibrations, frequent presence of pollutants and fumes, decreased line of sight and high airflows.

In an engine compartment, specific components may reach very high temperatures even during normal running conditions. Specifically the turbo charger and the exhaust system operates at high temperatures – 400°C to 550°C (Fournier 2004) – and may attain even higher temperatures in the case of malfunctioning or failed components. The presence of hot surfaces during normal running conditions will pose a challenge to any heat detectors or flame detectors.

The airflow in the engine compartment may also cause higher air temperatures further away from the hot surfaces. The airflow will dilute concentrations of soot particles and gases and cool the fire gases, delaying the fire detection. The airflow may also transport the soot particles or gases in an unwanted direction where no sensors are positioned.

Pollutants present in the compartment may deposit on flame detectors, obstruct the aspirating systems or saturate the filters of smoke detectors.

The frequent presence of exhaust fumes, vapours from oil or glycol on hot surfaces or diesel vapour, will pose a challenge to smoke and gas detectors causing false alarms.

The engine compartment will be filled with different components, and the line of sight for flame detectors could be blocked, delaying a rapid detection from flame detectors.

The environment in cab compartments will be less challenging compared with engine compartments, with fewer surfaces with higher temperatures. Still, if applying flame detectors the line of sight will have to be considered. The high likelihood of smouldering fires in electrical cables and installations will pose a challenge to smoke or gas detectors, accounting for the airflow in the cab.

Fire detection on the outer parts of the mining vehicle will pose a challenge due to the ventilation flow present in the mine drift. Smoke and gas detection will be difficult due to the dilution of the gases and smoke. The presence of smoke particulates and carbon monoxide from diesel equipment will add further to the difficulties. Possible methods could be flame detection and hot spot detection, focusing on likely positions such as the wheel/tyre area.

Data and methodology

Cone calorimeter tests

Cone calorimeter tests were performed at SP Fire Technology. Cone calorimeter tests allow for analysis regarding the behaviour of products when exposed to a radiant heat element (shaped as a cone). The heat element provides a uniform radiant heat flux to the sample, which is placed in a holder mounted on a load cell. Prior to the test, a desired heat flux is set, and a specified and consistent airflow is established through the cone calorimeter duct. The sample is placed below the cone shaped heater. A spark igniter is positioned above the sample surface, and a shutter (protecting the sample from the radiant heat flux) is opened, exposing the sample to the radiant heat flux and initiating the test. Upon ignition and the occurrence of a sustained flame, the spark igniter is deactivated. Throughout the test, the rising products of pyrolysis and combustion flow into an instrumented hood system above the cone heater. The products of pyrolysis, combustion as well as the oxygen concentration are analysed in the hood system, determining parameters such as the smoke production and heat release rate of the sample.

The cone calorimeter tests included a hydraulic hose, a low voltage cable and a section of the interior cab surface. The hydraulic hose was a Rockmaster/2SN ¼” 6.5 mm type hose. The cover of the hose consisted of synthetic rubber, the reinforcements of the hose consisted of two high tensile steel braids and the inner tube consisted of oil resistant synthetic rubber. The interior cab surface was a cut out section from an operator seat (see Figure 1 for the operator seat in question) consisting of foamed PVC. The low-voltage cable was a Buflex M $3 \times 95 + 3G16$ type cable, where the outer sheating consisted of flame retardant polyurethane. Figure 2 displays a prepared test sample of the low voltage cable prior to be fitted into a holder.

Electrical cables and hydraulic hoses will be found throughout most sections of a mining vehicle and the outer materials listed above are commonly found on cables and hoses in general.

The tests were conducted at three different incident heat flux values: 25, 35 and 50 kW/m^2. Table 1 lists and describes the output parameters from the conducted cone tests that were applied in the ensuing analysis. The output parameters were measured prior to as well as after the ignition of the sample, thus pre-ignition as well as fire data was recorded.

Figure 1. The operator seat from which a section was cut out. Images are available in colour online.

Figure 2. The low voltage cable prepared for the cone calorimeter test. Images are available in colour online.

Study of incident summaries from the mining industry in Western Australia

In order to analyse the detection of previously occurred fires in mining vehicles, a large number of incident summaries from the mining industry in Western Australia were studied. The Department of Mines, Industry Regulation and Safety at the Government of Western Australia provides incident reports open to the public. The incident reports date back to January 2010. The data is available to help the mining industry identify trends in safety performance and taking the necessary actions. The summaries specify the date of the incident and then continue with briefly describing the incident. The selected time period was January 2010 until August 2020 and incidents listed under category 'Outbreak of fire above or below ground' for both mining and exploration were extracted during the search in the database. No distinction was made with respect to the type of mine and whether the incident took place above or below ground. The large volume of extracted fire incidents was divided according to the type of vehicle where the fire started in, as the fire characteristics (fuel load, distribution of fuel load, types of combustibles, etc.) will vary between the different categories of vehicles. An earlier study comprising fire incidents in New South Wales, Queensland and Western Australia listed trucks, drill rigs, dozers and loaders as the most frequently found vehicle categories and the ensuing analysis was therefore focused at these four categories (Hansen 2018). The fire incidents for each vehicle category were then analysed with respect to how the fire was detected (signs or traces), whether any pre-ignition signs were noticed, part of vehicle where the fire occurred, fire cause, ignition source and fuel/s involved. When listing the location of the fire, the exhaust and turbo cases were merged into one group as it was difficult to clearly isolate these two locations (signs of a fire could be seen at the exhaust, but the actual fire took place in the turbo). When listing the type of fuel, hydraulic oil and oil were merged into one group, as it was difficult in many cases to discern whether it was oil or actually hydraulic oil that was listed in the summaries. Also, observe that the fire cause 'coolant onto a hot surface' will include oil as well as glycol as it was difficult to isolate these two types of fuels. The total number of fire incidents comprised in the analysis was 2567.

Table 1. Output parameters from the cone calorimeter tests.

Output parameter (unit)	Description of parameter
Time to ignition (s)	Point in time when a sustained flame occurred
Time to flameout (s)	Point in time when the sustained flame ceased
Heat release rate (kW/m^2)	Rate of energy released per unit burning specimen
Mass loss rate (g/s)	Mass loss rate of specimen degraded to produce combustible fuels
Specific extinction area (m^2/kg)	Ratio of smoke production to specimen mass loss
Carbon monoxide yield (kg/kg)	The mass of carbon monoxide produced per mass of specimen combusted
Carbon dioxide yield (kg/kg)	The mass of carbon dioxide produced per mass of specimen combusted
Mass flow rate (g/s)	Mass flow rate in the cone calorimeter duct downstream of the burning specimen
Light extinction coefficient (1/m)	The exponential reduction of light intensity by smoke obscuration
Volumetric flow rate in duct (L/s)	Volumetric flow rate in the cone calorimeter duct downstream of the burning specimen
Smoke production rate (m^2/s)	The instantaneous rate of light-obscuring smoke
Rate of smoke release ((m^2/s)/m^2)	The instantaneous rate of smoke release
Total smoke production (m^2)	The integrated smoke production rate over the test period
Total smoke release (m^2/m^2)	The integrated smoke release rate over the test period
Production rate of carbon monoxide (g/s)	The instantaneous rate of carbon monoxide produced
Production rate of carbon dioxide (g/s)	The instantaneous rate of carbon dioxide produced

Results and discussion

Pre-ignition and early fire traces and clues may be detected through the emission of decomposition products and heat or through occurring faults. The two former are analysed below, using data from the cone calorimeter tests involving solid materials typical of mining vehicles. The latter is analysed through incident summaries below by looking into faults such as emitted oil mist or loss of power.

Cone calorimeter tests

During the cone calorimeter tests three different incident heat flux values were applied: 25, 35 and 50 kW/m^2. A question here is what incident heat flux values should be focused on if investigating pre-ignition or early fire detection? Obviously, a lower incident heat

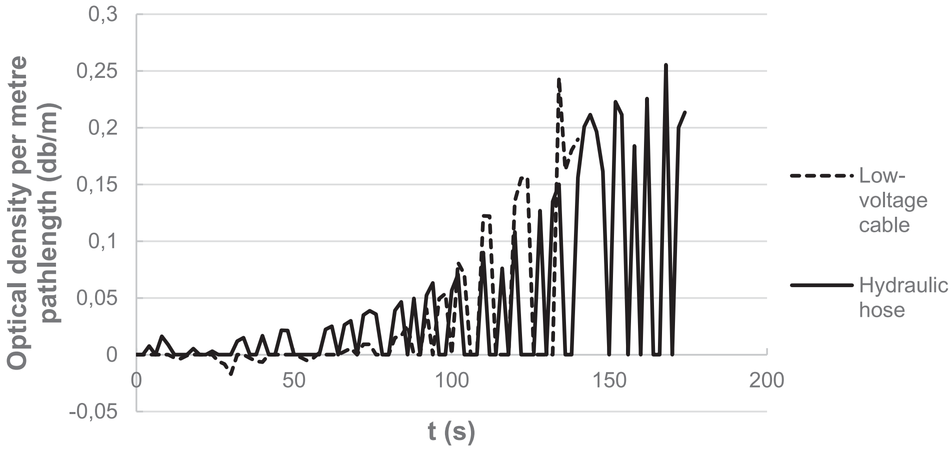

Figure 3. The optical density per metre pathlength prior to ignition. Images are available in colour online.

flux will correspond to a smaller ignition source or even a smoldering ignition source. An incident heat flux of 25 kW/m^2 may roughly correspond to a 0.25 m high and 0.1 m wide flame with a heat release rate of 25 kW. The heat release rate (per unit area) of a smoldering fire front ranges from 10 to 30 kW/m^2 (Ohlemiller and Shaub 1988). Hot surfaces in the engine compartment may attain temperatures of 550°C (Fournier 2004) and even higher. A surface temperature of 550°C will result in an emitted radiative heat flux of 26 kW/m^2. Even though the incident heat flux at a fuel surface will be less than 26 kW/m^2, any fuel surface very close to the hot surface may come close. Any loosened fuel item, coming close to a hot surface or unintentionally positioned on a hot surface may be exposed to an incident heat flux close to 25 kW/m^2. Thus, the focus in the ensuing analysis will be on the 25 kW/m^2 incident heat flux results. With the 25 kW/m^2 incident heat flux value, the time to ignition will increase and the chance to study pre-ignition traces and trends as well.

Different detector types will have different thresholds and activate differently depending on the type of sensor, type of combustion, etc. The following alarm thresholds were used in the ensuing analysis (Perera and Litton 2014):

- Smoke sensor: 0.044 db/m
- CO sensor: 10 ppm

Based on the data from the cone calorimeter tests, the optical density per metre pathlength D'_e (db/m) was calculated:

$$D'_e = \frac{SEA \cdot \dot{m}_{loss}}{\dot{V}} \tag{1}$$

where SEA is the specific extinction area (m^2/kg), $\dot{m}_{loss}$ is the specimen mass loss rate (kg/s) and $\dot{V}$ is the volumetric flow rate in the duct (m^3/s).

The optical density and the CO concentration will obviously vary with the airflow rate. The more or less fixed volumetric airflow rate of the cone calorimeter at 24 L/s may not necessarily be representative for an entire engine compartment. Still, the airflow rate could be feasible for a certain section of the engine compartment and the ensuing analysis will mainly have a qualitative approach – comparing the potential response of different sensor types for the given conditions.

Pre-ignition

Figure 3 displays the optical density per metre pathlength results for the 25 kW/m^2 incident heat flux involving the hydraulic hose and the electrical cable. The optical density of the cab interior was close to zero prior to ignition, where the specimen ignited relatively fast (i.e. after 12 s) for an incident heat flux of 25 kW/m^2. A smoke sensor would therefore not be a likely solution if trying to detect pre-ignition conditions involving cab interior material. If applying the threshold of 0.044 db/m it can be seen that for a hydraulic hose a smoke sensor would activate an alarm after 84 s, which is 90 s prior to ignition. For an electrical cable, a smoke sensor would activate an alarm after 96 s, which is 44 s prior to ignition.

The longer ignition times of the electrical cable (140 s) and the hydraulic hose (175 s) for the 25 kW/m^2 case will increase the likelihood of ample time for actions such as shutting down the vehicle upon detection.

The CO concentration results for the 25 kW/m^2 incident heat flux involving the hydraulic hose and the electrical cable is seen in Figure 4. An alarm threshold of 10 ppm CO would result in an alarm activation after 140 s (electrical cable) and 174 s (hydraulic hose), which is more or less equivalent to the ignition times. A CO sensor would thus provide a poor pre-ignition detection solution for the electrical cable and hydraulic hose. The corresponding CO concentration for the cab interior is seen in Figure 5. As opposed to a smoke sensor, a CO sensor could potentially provide a pre-ignition detection in the case of the

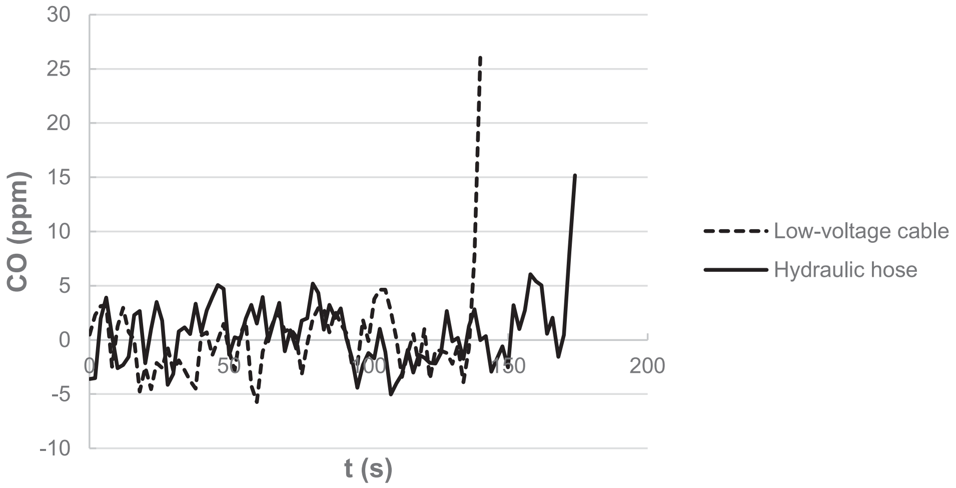

Figure 4. The CO concentration of the electrical cable and hydraulic hose prior to ignition. Images are available in colour online.

cab interior. An alarm threshold of 10 ppm would result in an alarm activation after 6 s, which is 6 s prior to the ignition. The time period between alarm activation and ignition is short and given the transport time for the CO to reach the sensor, the actual time available is even shorter. However, with a heat source resulting in a lower incident heat flux the time period available would increase further. Still, a flashy fuel such as the cab interior with short ignition times (ignition took place after 12, 5 and 3 s for the 25, 35 and 50 kW/m^2 heat flux respectively) will pose a challenge when it comes to pre-ignition detection.

The heat release rates of the three specimens can be found in Figure 6. Both the electrical cable and the hydraulic hose display heat release rates meandering around zero during throughout most of the pre-ignition phase. Only a few seconds prior to ignition can the heat release rate be seen to clearly increase. The cab interior displays a different behaviour, with a clearly increasing heat release rate several seconds prior to ignition. This rapid increase in heat release rate could be taken advantage of, positioning heat detectors in the cab compartment; preferably rate-of-rise type heat detectors to match the rapid increase in heat release rate. Even though heat detection may not be possible pre-ignition due to transport time to heat detector, unfavourable airflow, etc., with a continued increase in heat release rate post-ignition, an early detection could still be a possibility.

Given the results from the cone calorimeter, smoke sensors could potentially be used for pre-ignition detection in a cab compartment involving electrical cables as fuel. If overcoming the challenges of the environment, smoke sensors could also be a potential pre-ignition detector in engine compartments involving hoses or electrical cables. CO sensors and rate-of-rise type heat detectors could be a possibility in the cab compartment involving the cab interior.

Post-ignition

If the cab interior displayed an optical density close to zero prior to ignition, the opposite occurs post-ignition as can be seen in Figure 7. The optical density of the cab interior rises to values well above 2 db/m almost instantaneously upon ignition. The optical

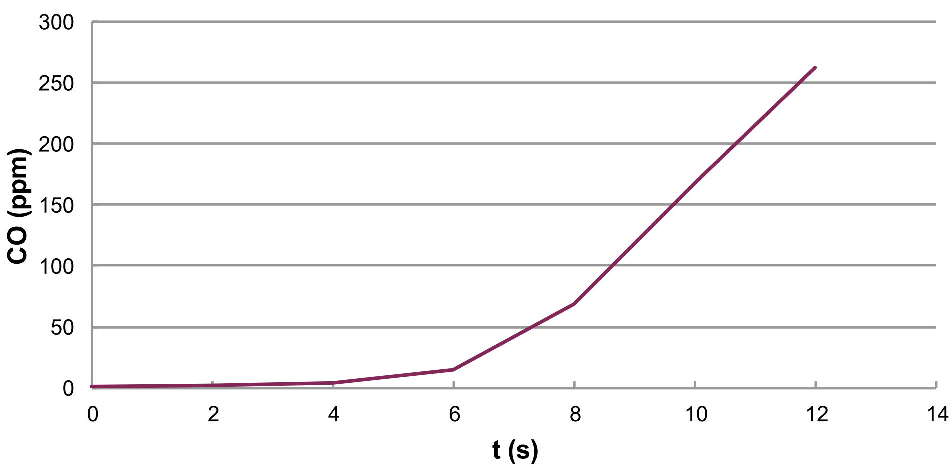

Figure 5. The CO concentration of the cab interior prior to ignition. Images are available in colour online.

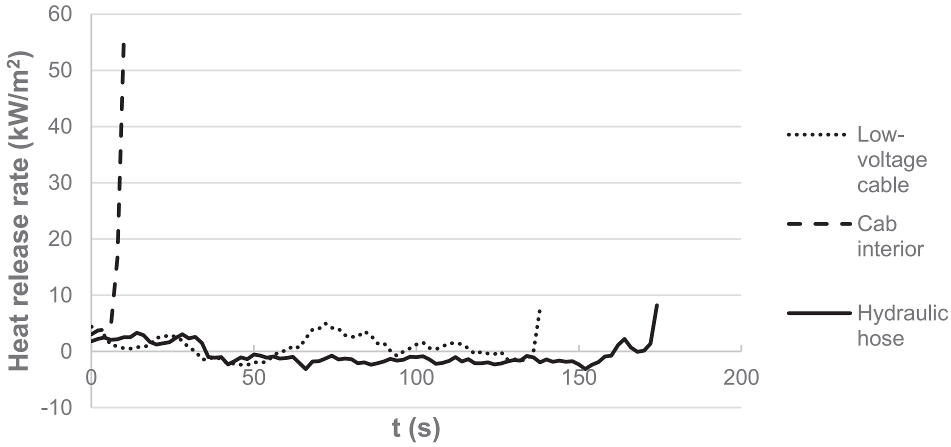

Figure 6. The heat release rate prior to ignition. Images are available in colour online.

density subsequently decreases but still lingers in the 1 db/m region throughout most of the fire duration.

The hydraulic hose also displays a rapid rise up to the vicinity of 6 db/m, although not as rapid as for the cab interior. The rapid increase follows by an equally rapid decrease. Already 5 min after ignition the optical density values fall short of the alarm threshold.

The electrical cable displays a different development with a slower growth up to 3 db/m after 3 min, followed by a slow decline.

Given the rapid increase in the optical density, the post-ignition scenario involving the cab interior and the hydraulic hose would be suitable for a smoke sensor.

The cab fire experiments conducted by De Rosa and Litton (2010) showed that smoke detectors positioned in the cab were efficient when detecting small pool fires down to 0.05 kW but also small smouldering fires. The pool fires were aimed at simulating spray fires penetrating the cab. The use of smoke sensors in cab compartment could thus cover fires in several types of fuel.

The post-ignition developments of the CO concentration can be found in Figure 8. The CO concentration of the cab interior displays a similar development compared with the optical density: an instantaneous rise towards 400 ppm followed by a rapid decrease and a slow decaying phase, where the 10 ppm threshold is never fallen short of.

Initially, the hydraulic hose displays a rapid increase in the CO concentration attaining a maximum value at approximately 300 ppm. After attaining the peak value the concentration decreases rapidly, levelling out at 50 ppm.

The electrical cable displays a different development compared with the smoke density: a very rapid increase attaining a peak value at 450 ppm followed by a rapid decrease to 300 ppm and a slow decaying phase.

In a post-ignition scenario, a CO sensor would be suitable for the cab interior and the electrical cable.

The heat release rates of the three specimens can be found in Figure 9. The rapid increase to higher levels of heat release rate of the electrical cable and the hydraulic hose further emphasizes the need for early

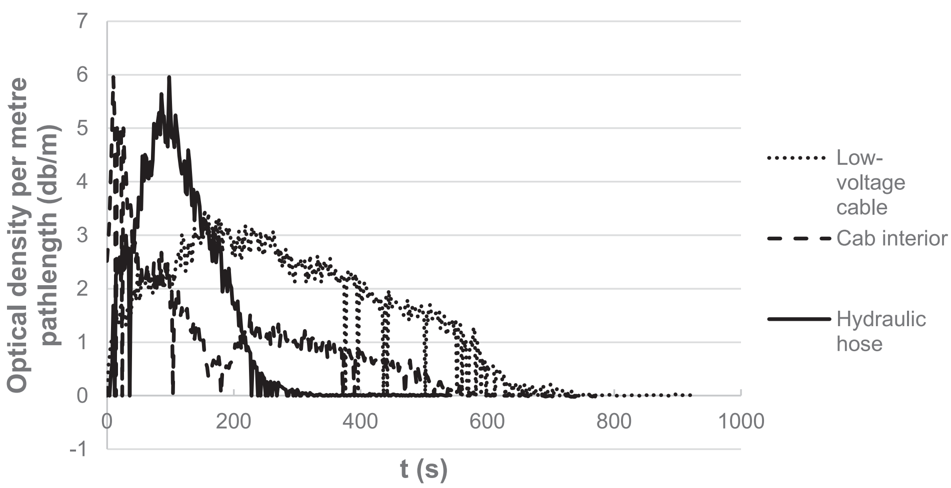

Figure 7. The optical density per metre pathlength after ignition. Images are available in colour online.

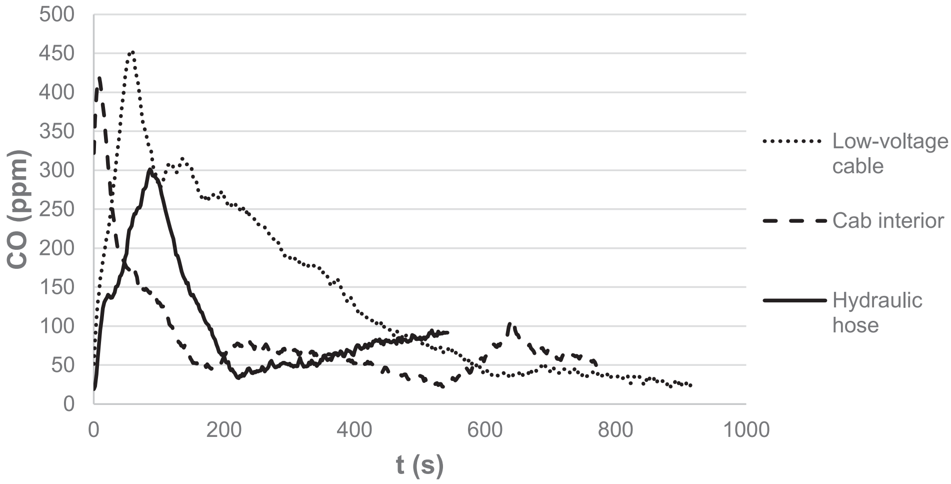

Figure 8. The CO concentration after ignition. Images are available in colour online.

detection. Even though the cab interior specimen displays a lower peak heat release rate, the specimen displays a more rapid fire growth rate compared with the cable and the hose (continuing from the pre-ignition phase). This very rapid fire growth rate could be taken advantage of, applying heat sensors or possibly flame detectors in the cab compartment. As mentioned earlier, rate-of-rise type heat detectors could fit the rapid fire growth rate very well. A flame detector would have the advantage of instantaneous detection – not depending on any transport time – which could lead to a faster detection than a CO sensor in the pre-ignition phase. The suitability of a flame detector in the case of cab fires is in line with the cab fire experiments conducted by De Rosa and Litton (2010). A flame detector in the experiments was found to efficiently and rapidly small pool fires – simulating spray fires – in the cab compartment. Despite the somewhat slower fire growth rates of the cable and the hose, the distinctly increasing heat release rates of the two specimens to higher levels could also be used for heat detection in a post-ignition scenario.

Given the results from the cone calorimeter, the cab compartment could be equipped by smoke sensors, CO sensors, rate-of-rise type heat detectors and flame detectors to detect post-ignition fires involving cab interior and CO sensors and heat detectors involving electrical cables. The engine compartment could be protected by smoke sensors and heat detectors to detect fires in hoses. CO sensors could be applied to detect fires in electrical cables.

As noted the pre-ignition detection and the post-ignition detection will likely involve several types of sensors in a compartment given the various types of fuel but also the subtle traces and the pros and cons of the sensor operability.

Detection of other gas compounds – electrical cables and hydraulic hoses

During the cone calorimeter tests, the only gas compounds measured were oxygen, carbon monoxide and carbon dioxide. The gases emitted during the pre-ignition phase may be numerous and will vary depending on the material. Gas detection could potentially be used for pre-ignition detection in

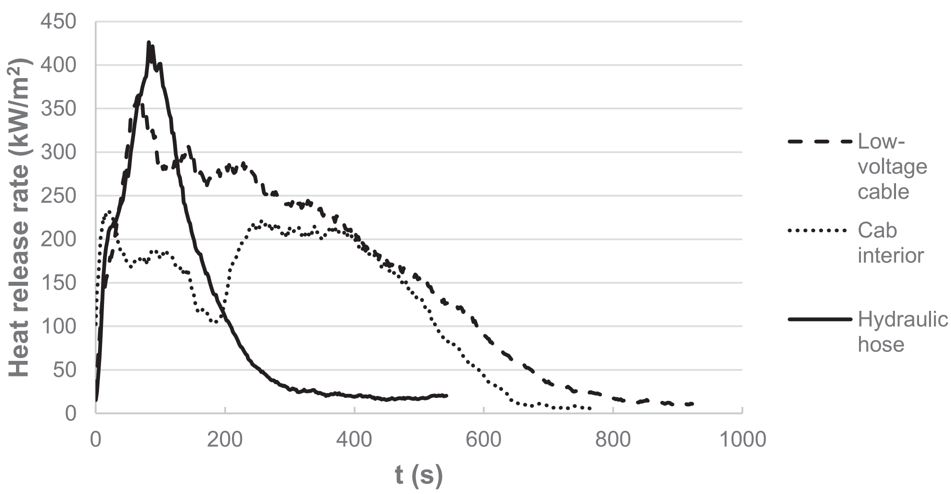

Figure 9. The heat release rate of the three specimen. Images are available in colour online.

compartments, as a gas compound not otherwise present will be a distinct trace. Obviously, an analysis on the specific vehicle type will have to be conducted, investigating the type of materials present and emitted gas compounds and the environment in the compartment.

The emitted gases from electrical cables during the pre-ignition phase will vary depending on the composition of the cable insulation materials. Earlier studies (Liu and Kim 2003; Aracil et al. 2005) have found that typical pyrolysis gases from cable insulation materials are CO, propene and methane. Grayson et al. (2000) conducted a large number of experiments on the fire performance of electrical cables. The gases encountered and measured during the experiments were CO_2, CO, HCl and in one case HF.

The outer surface of the hydraulic hoses will often consist of nitrile-butadiene rubber.

Saha and Bowmick (2017) performed experiments on acrylonitrile–butadiene model compounds to determine the thermal decomposition characteristics. Besides the H_2 and CO being the most common gases released from the pyrolysis process, the other most common fragments were identified as 1,3-butadiene, acrylonitrile, 2-butene and 3-butenenitrile. Fuh and Wang (1998) performed an analysis on the pyrolysis of nitrile rubber and found common fragments to be 1,3-butadiene, 2-propenenitrile, benzene and toulene.

Incident summaries

The following groups of initially observed fire traces or occurring faults were distinguished among the summaries:

- Visual observation of flames
- Visual observation of smoke, smelt smoke or noticed burning smell
- Operator noticed that the vehicle malfunctioned, lost power, lost control or could not be started
- Visual observation of oil spray or oil leak
- Visual observation of leaking diesel
- Visual observation of flames and smoke more or less simultaneously
- Operator or personnel nearby heard a noise or a bang
- Visual observation of sparks
- Operator was notified by alarm or warning signal
- The vehicle shut down
- Operator or personnel nearby smelt oil
- Operator or personnel nearby smelt diesel
- Visual observation of a short circuit flash or arcing
- The fire suppression system activated

As noted from the list above, no fires were detected by a designated fire detection system (if excluding the activation of a suppression system). Instead, the fire detection relied heavily on the operator or personnel nearby observing fire traces or occurring faults. An analysis of the summaries could therefore include suggestions on fire detection measures for specific vehicle parts or vehicle types, potentially providing earlier fire detection.

In a number of summaries, the detected fire traces or occurring faults were not specified. Simply stating that the fire was noticed or detected but not how.

Table 2 lists the number of cases and the percentage (of the total cases) of the initially detected fire traces or occurring faults. The two most common fire traces were the observation of smoke and flames respectively. The smoke observation cases amounts to somewhat more than the flame observation cases, which nevertheless tells us that a fairly large amount of the cases are detected late and not pre-ignition (flames occurring at the time of ignition). At the other end of the scale, the operator smelling smoke could be regarded as favourable in many cases as the human nose could be very sensitive to smoke, possibly providing pre-ignition detection.

It would thus be of interest to look into the flame detection cases for the different vehicle categories, to see whether measures could be taken to speed up the detection. Another interesting feature of Table 2 is that the malfunction of vehicle and oil spray/leak are commonly occurring traces and faults, which could possibly be used for pre-ignition detection. The most common positions of the occurring fires would also be interesting to study, providing fire detection for a majority of the fires.

Table 2. The frequency of initially detected fire traces or occurring faults.

Fire trace or occurring fault	Number of cases	Percentage of total number
Visual observation of smoke, smelt smoke or noticed burning smell	635	24.7
Visual observation of flames	548	21.4
Operator noticed that the vehicle malfunctioned, lost power, lost control or could not be started	197	7.7
Visual observation of flames and smoke more or less simultaneously	192	7.5
Visual observation of oil spray or oil leak	163	6.3
Operator or personnel nearby heard a noise or a bang	98	3.8
Operator was notified by alarm or warning signal	88	3.4
Visual observation of sparks	70	2.7
The fire suppression system activated	46	1.8
The vehicle shut down	33	1.3
Operator or personnel nearby smelt oil	14	0.5
Visual observation of leaking diesel	13	0.5
Visual observation of a short circuit flash or arcing	6	0.2
Operator or personnel nearby smelt diesel	1	0.1
Not specified	463	18.1

Trucks

The most commonly detected initial fire traces or occurring faults were:

- Visual observation of smoke, smelt smoke or noticed burning smell: 280 cases
- Visual observation of flames: 267 cases
- Visual observation of flames and smoke more or less simultaneously: 104 cases
- Operator noticed that the vehicle malfunctioned, lost power, lost control or could not be started: 97 cases
- Operator or personnel nearby heard a noise or a bang: 54 cases
- Visual observation of sparks: 50 cases
- Operator was notified by alarm or warning signal: 38 cases

When comparing the cases detected by the flame with the cases detected by the smoke, it was found that a larger number of cases occurred in the turbo/exhaust area, starter motor and grid box in the flame detection cases. If analysing further the flame detection cases at these three positions, it was found that the most common fire cause scenarios at the exhaust/turbo were either oil onto a hot surface or solid onto a hot surface. Solid materials in these cases were mostly represented by coolant hoses or forgotten rags. The early detection of oil onto a hot surface could include gas sensors detecting the emitted hydrocarbons or an oil mist detection system. As hydrocarbons may be constantly present in an engine compartment, the threshold will have to be carefully set to minimize false alarms. The results and discussion from the cone calorimeter experiments could be applied in the case of a solid onto a hot surface. In both the starter motor and grid box cases, the most common fire cause scenarios were electrical fault and overheating. The electrical faults could possibly be detected by, for example, a circuit detection device and the overheating scenario could be detected by an infrared camera aimed at the potential hot spot or by installing temperature sensors with pre-defined temperature thresholds (shutting down at higher temperatures).

In the cases where the vehicle malfunctioned, lost power, etc., it was found that other than the positions listed above, the engine compartment, cab, brakes and wheel/tyre area were also frequently found in the summaries. An electrical fault was frequently found among the fire causes in the engine compartment (besides the oil onto hot surface scenario) and the cab compartment. The recommendations from the cone calorimeter experiments (electrical cable) together with a circuit detection device and gas sensors could potentially be used in these cases. For the brake and wheel/tyre areas, the common denominator was failed component resulting in overheating.

The cases where the initial trace consisted of a noise, a bang, alarm/warning notification or sparks showed identical fire positions and fire scenarios as listed above. The grid box area was the most common fire position in the spark cases and an electrical fault the most common fire cause.

Overall, the most common positions of the occurring fires were turbo/exhaust, engine compartment followed by the wheel/tyre area and brakes, which are all listed and discussed above. The post-ignition detection in the turbo/exhaust and engine compartment could take advantage of the sooty flames from fires in oil or diesel. A smoke sensor system or a flame detection system triggered by the electromagnetic radiation emitted by the soot could be an option.

Drill rigs

The most commonly detected initial fire traces or occurring faults were:

- Visual observation of smoke, smelt smoke or noticed burning smell: 148 cases
- Visual observation of flames: 140 cases
- Visual observation of oil spray or oil leak: 88 cases
- Operator noticed that the vehicle malfunctioned, lost power, lost control or could not be started: 41 cases
- Visual observation of flames and smoke more or less simultaneously: 35 cases
- Operator or personnel nearby heard a noise or a bang: 29 cases
- The vehicle shut down: 20 cases

When comparing the cases detected through the flame with the cases detected through the smoke, it was found that a larger number of cases occurred in the turbo/exhaust area in the flame detection cases. The most common fire cause scenarios at the exhaust/turbo were either diesel onto a hot surface or oil onto a hot surface. Same as for the truck cases, the diesel onto hot a surface scenario could potentially be detected by gas sensors detecting the emitted hydrocarbons from the gassing.

In the cases where an oil leak or spray was observed, the vehicle shut down or where the vehicle malfunctioned, lost power, etc., a clear majority of the cases occurred in the exhaust/turbo region or the engine bay and oil onto a hot surface was the dominating fire cause. In the cases where the initial trace consisted of a noise or a bang, the compressor and receiver tank – other than the exhaust/turbo region and engine bay – were frequently found in the summaries. A flash fire was the most common fire scenario involving the compressor and receiver tank. A flash fire could be detected early – possibly prior to ignition – by applying gas sensors in the compressor and receiver tank area, detecting gaseous products from flammable liquids with lower flashpoints.

Overall, the most common positions of the occurring fires were turbo/exhaust, engine compartment followed by the compressor/receiver tank and the starter motor. Overheating or an electrical fault was the most frequent fire scenarios involving a starter motor. The post-ignition detection of a flash fire in the compressor/receiver tank could consist of a flame detector system where the triggered wavelengths should be selected depending on the products from the fire.

Dozers

The most commonly detected initial fire traces or occurring faults were:

- Visual observation of smoke, smelt smoke or noticed burning smell: 120 cases
- Visual observation of flames: 64 cases
- Visual observation of oil spray or oil leak: 33 cases
- Operator noticed that the vehicle malfunctioned, lost power, lost control or could not be started: 20 cases
- Visual observation of flames and smoke more or less simultaneously: 19 cases

The number of cases where the flame was initially detected was much smaller than the cases where smoke was initially noted. When comparing the cases detected by the flame with the cases detected by the smoke, no fire position was overrepresented among the flame detection cases.

In the cases where an oil leak or spray was observed, a clear majority of the cases occurred in the exhaust/turbo region or the engine bay and oil onto a hot surface was the dominating fire cause. In the cases where the initial trace consisted of a malfunctioning vehicle, losing power, etc., the starter motor – other than the exhaust/turbo region and engine bay – were frequently found in the summaries. An electrical fault or overheating was the most common fire scenarios involving a starter motor.

Overall, the most common positions of the occurring fires were turbo/exhaust, engine compartment followed by the starter motor.

Loaders

The most commonly detected initial fire traces or occurring faults were:

- Visual observation of smoke, smelt smoke or noticed burning smell: 87 cases
- Visual observation of flames: 81 cases
- Operator noticed that the vehicle malfunctioned, lost power, lost control or could not be started: 39 cases
- Visual observation of flames and smoke more or less simultaneously: 34 cases
- Operator was notified by alarm or warning signal: 23 cases

When comparing the cases detected by the flame with the cases detected by the smoke, no fire position was overrepresented among the flame detection cases.

In the cases where the initial trace consisted of a malfunctioning vehicle, losing power, etc., the starter motor, the exhaust/turbo region and engine bay were frequently found in the summaries. An electrical fault or overheating was the most common fire scenarios involving a starter motor. Oil onto a hot surface was the dominating fire scenario involving the exhaust/turbo area and the engine bay.

In the cases where the initial trace consisted of an alarm/warning notification, the alternator and the engine bay dominated among the fire positions. Oil onto a hot surface and electrical fault were the most frequent fire scenarios for the engine bay and a failed bearing resulting in overheating for the alternator scenarios. Temperature sensors or an infrared camera could be used for overheating detection, shutting down the vehicle above a threshold temperature.

Overall, the most common positions of the occurring fires were turbo/exhaust, engine compartment followed by the alternator and the starter motor.

Remote operated vehicles

As mentioned before, the fire detection relied heavily on the operator or personnel nearby observing fire traces or occurring faults. What happens when the vehicle is remote operated using a tele-remote camera? When studying the summary cases with remote operated vehicles it was found that more than twice as many fires were detected by visual observation of flames compared with the visual observation of smoke. Even the number of cases where the fire was detected by warning signal, malfunction, lost signal, etc. outnumbered the cases detected through the smoke. When remotely operating a vehicle, the operator loses some of the potential detection modes: smelling smoke or burning and feeling vibrations, shocks and other possibly deviating movements. The human nose is highly sensitive and may detect smoke at a very early stage, thus with a remote operated vehicle an essential detection tool is lost.

In addition, the visual observation using a tele remote camera may decrease the ability to detect smoke during the incipient phase (possibly explaining why flame detection dominated among the cases). As mentioned in the fire behaviour section, the initially emitted smoke of an incipient phase fire may have a laminar type of flow, which will be more difficult to discern with a camera compared with a more turbulent smoke flow.

Clearly, the need for a designated pre-ignition and early fire detection system will increase for remote operated vehicles.

The design of the mining vehicle – aiding the fire detection

When designing for example the engine compartment or a cab of a mining vehicle, obstructions, geometry of the compartment, temperature variations, airflows and the environment should be analysed and possibly altered to allow for an early fire detection. The design of the vehicle could also be aimed at mitigating the sensitivity issues of various fire sensors.

The choice of material could also aid the fire detection system, selecting material, which will emit products favourable for the selected type of fire sensor/s.

Future research

With the introduction of battery driven vehicles in the mining industry, the need for pre-ignition detection increases as the fire suppression can be complicated and require considerable resources.

The pre-ignition detection should be focused on early detection of thermal runaway. Warning systems already exist but as the number of battery driven vehicles will most likely increase in the mining industry, further research should be conducted.

Experiments should be conducted in a compartment, involving gas detection of hydrocarbons emitted due to gassing of oil on a hot surface.

Experiments should be conducted in vehicle compartments, involving feasible ignition sources and fuels – taken from the incident summaries – testing for example the pre-ignition detection of gas compounds or oil mist. An electronic nose could with advantage be tested for multi gas detection.

Experiments on remote operated vehicles should be conducted where a video image detection system is used for early detection of smoke on the exterior of the vehicle. The system takes advantage of emerging computer processing and image analysis technologies. The technology could potentially mitigate the loss of detection modes in the absence of an operator.

Further studies into the design of mining vehicles and the selection of materials should be conducted, aiding the early fire detection.

Conclusions

A study on the pre-ignition detection and early fire detection on mining vehicles was performed. Data from cone calorimeter tests and incident summary data were applied when analysing possible fire detection solutions on mining vehicles.

It was found that the results from the cone calorimeter tests indicated that smoke sensors could potentially be used for pre-ignition detection in a cab compartment involving electrical cables as fuel. If overcoming the challenges of the environment, smoke sensors could also be a potential pre-ignition detector in engine compartments involving hoses or electrical cables. CO sensors and rate-of-rise type heat detectors could be a possibility in the cab compartment involving the cab interior. In the post-ignition case the cab compartment could be equipped by smoke sensors, CO sensors, rate-of-rise type heat detectors and flame detectors to detect fires involving cab interior and CO sensors and heat detectors involving electrical cables. The engine compartment could be protected by smoke sensors and heat detectors to detect fires in hoses. CO sensors could be applied to detect fires in electrical cables.

The major findings from the incident summaries were that a larger number of cases with late detection occurred in the turbo/exhaust area, engine compartment, starter motor and grid box (truck category). The most common fire cause scenarios at the exhaust/turbo and the engine compartment was oil onto a hot surface. The early detection of oil onto a hot surface could include gas sensors detecting the emitted hydrocarbons or an oil mist detection system. The post-ignition detection in the turbo/exhaust and engine compartment could be a smoke sensor system or a flame detection system triggered by the electromagnetic radiation emitted by the frequent soot particles. In both the starter motor and grid box cases, the most common fire cause scenarios were electrical fault and overheating. The electrical faults could possibly be detected by, for example, a circuit detection device and the overheating scenario could be detected by an infrared camera or by installing temperature sensors.

Other identified risk areas included the brake and wheel/tyre area (truck category), the alternator (loader category) and the compressor/receiver tank (drill rig category). The common denominator in the brake, wheel/tyre and alternator cases was failed component resulting in overheating, which could be detected by an infrared camera or by temperature sensors. A flash fire was the most common fire cause in the compressor and receiver tank area. A flash fire could be detected early by applying gas sensors, detecting gaseous products from flammable liquids with lower flashpoints. The post-ignition detection could consist of a flame detector system.

The pre-ignition and post-ignition in a compartment could include several types of sensors depending on the types of fuel, ignition sources, etc. found in the compartment. The design process will most likely be limited to the most common fire scenarios of the compartment and cases where an early detection is crucial for the outcome.

The increased knowledge and focus on pre-ignition and early fire detection could potentially improve the fire safety in the mining industry.

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References

Aracil I, Font R, Conesa JA. 2005. Semivolatile and volatile compounds from the pyrolysis and combustion of polyvinyl chloride. J Anal Appl Pyrol. 74:465–478.
Buchanan AH. editor. 2001. Fire engineering design guide. Centre for Advanced Engineering. Christchurch: University of Canterbury.
Bukowski RW. 1995. Predicting the fire performance of buildings: establishing appropriate calculation methods for regulatory applications. Proceedings of the 1st International Conference on fire Science and Engineering; Kowloon, Hong Kong. p. 9–18.
Charumporn B, Omatu S, Yoshioka M, Fujinaka T. 2004. Fire alarm systems using electronic nose systems. IFAC Workshop on Adaptation and Learning in Control and Signal Processing, and IFAC Workshop on Periodic Control Systems, Yokohama, Japan, August 30–September 1, p. 219–223.
Collier PCR, Whiting PN. 2008. Timeline for incipient fire development. Study report No. 194, BRANZ, Judgeford, New Zealand.
Conti R. 1992. Detection of underground mine fires. MST Annual Conference on fire Research; Rockville, Maryland. p. 31–32.
Conti RS, Litton CD. 1995. A comparison of mine fire sensors. Report of Investigations 9572, Bureau of Mines, United States Department of the Interior.
De Rosa MI. 2004. Analysis of mine fires for all US metal/non-metal mining categories, 1990–2001. NIOSH.
De Rosa MI, Litton CD. 2010. Rapid detection and suppression of mining equipment Cab fires. Fire Technol. 46:425–435.
Fitzgerald RW. 2004. Building fire performance analysis. Chichester: Wiley.
Fournier E. 2004. Under hood temperature measurements of four vehicles. Ottawa: MVFRI.
Fuh M-RS, Wang G-Y. 1998. Quantitative analysis of nitrile rubber/chloroprene by pyrolysis/gas chromatography/mass spectrometry. Anal Chim Acta. 371:89–96.
Grayson SJ, Van Hees P, Vercellotti U, Breulet H, Green A. 2000. Fire performance of electrical cables – new test methods and measurement techniques. Final Report on the European Commission SMT Programme Sponsored Research Project SMT4-CT96-2059, Interscience Communications Limited.
Hansen R. 2009. Literature survey–fire and smoke spread in underground mines. Mälardalens Högskola, MdH SiST 2009;2. Västerås.
Hansen R. 2018. Fire statistics from the mining industry in New South Wales. Queensland: The University of Queensland.
Litton CD. 2002. The use of light scattering and ion chamber responses for the detection of fires in diesel contaminated atmospheres. Fire Saf J. 37:409–425.
Litton CD, Perera IE. 2012. Evaluation of criteria for the detection of fires in underground conveyor belt haulageways. Fire Saf J. 51:110–119.
Liu Z, Kim A. 2003. Review of recent developments in fire detection technologies. J Fire Prot Eng. 13:129–151.
Ohlemiller T, Shaub W. 1988. Products of wood smolder and their relation to wood-burning stoves. NBSIR 88-3767. Washington, DC: National Bureau of Standards.
Perera IE, Litton CD. 2011. A detailed study of the properties of smoke particles produced from both flaming and non-flaming combustion of common mine combustibles. Proceedings of the 10th International Symposium on Fire Safety Science. College Park (Maryland): International Association for Fire Safety Science. p. 213–226.
Perera IE, Litton CD. 2014. Evaluation of smoke and gas sensor responses for fires of common mine combustibles. Trans Soc Min Metall Explor Inc. 336:381–390.
Ristić JD. 2001. Problems and actual solutions in quantitative fire hazard analysis. Work Living Environ Prot. 2:59–68.
Saha T, Bowmick AK. 2017. High-temperature pyrolysis simulation of acrylonitrile-butadiene model compound with experimental evidence. J Anal Appl Pyrolysis. 125:243–257.
Sundström B., editor. 1995. Fire safety of upholstered furniture – the final report on the CBUF research programme. London: European Commission Measurement and Testing Report EUR 16477 EN.
Yuan L, Thomas RA, Rowland JH, Zhou L. 2018. Early fire detection for underground diesel fuel storage areas. Process Saf Environ Prot. 119:69–74.