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ABSTRACT

This report includes the Proceedings of the 4th International Conference on Fires in Vehicles – FIVE 2016, held in Baltimore, October 5-6, 2016. The Proceedings includes 20 papers given by speakers in six sessions called, The fire problem, Alternative fuel vehicles, Fire development, Fire safety, Fire investigations and Fire protection. A poster exhibition accompanied the sessions. The extended abstracts on the posters are included in the proceedings together with the papers of the invited keynote speakers that opened each day.

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PREFACE

These proceedings include papers and extended abstracts from the 4th International Conference on Fires in Vehicles – FIVE 2016, held in Baltimore October 5-6, 2016. The proceedings include an overview of research and regulatory actions coupled to state-of-the-art knowledge on fire related issues in passenger cars, buses, coaches, trucks and trains.

Fires in transport systems are a challenge for fire experts. New fuels that are efficient and environmentally friendly are rapidly being introduced together with sophisticated new technology such as e.g. fuel cells. This rapid development, however, introduces new fire risks not considered previously and we risk a situation where we do not have sufficient knowledge to tackle them. In this context FIVE represents an important forum for discussion of the fire problem and for exchange of ideas.

Fire protection in road, rail, air, and sea transport is based on international regulations since vehicles cross borders and the safety requirements must be the same between countries. Therefore understanding of safety and regulations must be developed internationally and the FIVE-conference has a significant role to play as a place to exchange knowledge.

FIVE attracts high attendance of experts, researchers, operators, manufacturers, regulators and other key stakeholders. Of particular value is the mix of expertise and the international participation in the conference. The conference is unique as it includes fires in different vehicles. It is not confined to bus fires or train fires but includes them both, naturally since fire problems are often similar regardless of type of vehicle. This means that for example solutions for trains are useful for fire problems in buses and vice versa.

In the proceedings you will find papers on the fire problem, alternative fuel vehicles, fire development, fire safety, fire investigations and finally fire protection vehicles. We are grateful to the renowned researchers and engineers presenting their work and to the keynote speakers setting the scene. We sincerely thank the scientific committee for their expert work in selecting papers for the conference.

We would also like to take this opportunity to thank our event partner NFPA for the co-operation and invaluable help to realize FIVE 2016 in the wonderful city of Baltimore.

Björn Sundström
Chair FIVE 2016

Petra Andersson
Chair FIVE 2016 Scientific Committee

Note: the views expressed in the papers are those of the authors and not necessarily those of SP Technical Research Institute of Sweden, Department of Safety.
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Progress in Fire Safety Issues for E-Vehicles and the Challenges Ahead

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ABSTRACT
Electric vehicles and hybrid electric vehicles, a.k.a., e-vehicles, are seeing a resurgence on roadways across the world. As new vehicles based on electrical power sources proliferate, questions exist from emergency responders and others as to how well safety concerns are addressed relating to these new vehicles, their components, and the supporting technology in the built infrastructure.

Every day, engineers and researchers work to address fire protection challenges, but our world today is often unwittingly creating new problems—a direct result of the technologies, approaches, and alternative methods we generate. This is partially true of e-vehicles and their associated technology, and in particular, lithium ion batteries that have likewise proliferated as the selection of choice for electrical energy storage. The concerns for safety extend beyond simply a damaged vehicle on the roadway, and includes other challenging scenarios such as a vehicle fire within a parking garage, victim extrication from a submerged vehicle, bulk storage/transport of lithium ion batteries, and second life use of batteries for electrical energy storage.

Multiple research projects and consensus-building networking conferences have been conducted as e-vehicles have proliferated, and this has helped stay ahead of adverse events in a proactive rather than reactive manner. As technology evolves, it is introducing a future with new challenges as well as new solutions. Examples of the changing landscape includes: high-strength light-weight alloy vehicle bodies, new high energy-density electrical battery designs, massless battery technology, and vehicle telematics.

As e-vehicles and their related technologies continue to evolve and the fruits of their intended purpose flourish, society must continue to be vigilant for possible hazards, wise enough to understand the implications of failure, and courageous enough to be proactive stewards in the name of safety.

KEYWORDS: electric vehicle, hybrid electric vehicle, e-vehicle, emergency, emergency responders, fire, fire fighter, lithium ion battery

INTRODUCTION AND BACKGROUND
Around the 2008 time frame, the beginning of the Obama administration and other influencing factors (e.g., alleviate the dependence on foreign energy resources) provided a renewed focus to address the inherent fire protection and emergency responder safety concerns relating to the proliferation of e-vehicles. Since then we have benefited from multiple research studies, conferences, summits, and training programs in support of alternative fuel vehicles such as e-vehicles.

A proactive approach has been and continues to be in everyone’s best interest. Staying out of the mainstream news with unwanted “bad news” stories is paramount to the continuing successful roll-out of e-vehicle technology. The underlying intent of the various safety oriented programs is to support the proliferation of these vehicles and associated technology by addressing unwanted fires and other emergency events before they occur, and effectively and efficiently mitigating them if and once they do. Today’s world is hyper-sensitive to bad press and unfortunate news, and the vehicle industry is no exception from its unwanted influence.
From the standpoint of emergency responders, they are already well familiar with traditional internal combustion engine vehicles involved in a typical emergency incident. From their standpoint, newer technology vehicles raise the simple question: “what’s different?”

These technologies are providing significant improvement in vehicle efficiencies, but at the same time they are introducing new potential hazards requiring tactical adjustments and a need for awareness by emergency responders and other safety professionals. The landscape of modern automotive vehicles is evolving, and large format lithium ion batteries are considered to be the most popular of the available technologies serving as an alternative to internal combustion engine powered vehicles.

As mentioned earlier, fire departments and fire brigades are already familiar with fighting traditional vehicle fires as an expected part of their normal duties and tasks. These are among the more common fires they handle, as represented by annual U.S. fire incident data that indicates approximately 164,000 highway vehicle fires occurred in 2011 with 300 civilian deaths and 925 civilian injuries.[1] It is realistic for a typical fire fighter to face a highway vehicle fire at least once during their career.

From the perspective of national fire loss data, passenger road vehicles are considered to be those designed for transporting people using roads, and include cars, buses, recreational vehicles, and motorcycles. Truck/freight road vehicles include pick-up trucks and larger transport vehicles.[2] The most common highway vehicles involved in fires are passenger vehicles, accounting for over 70 percent of the highway vehicle fires in the United States during the five year span of 2003 to 2007.[3] Vehicle fires that occur in the open (e.g., not within a garage or building) are generally classed as highway vehicle fires in the statistical literature.[4]

An important early information gathering study was conducted in 2009 and 2010 that set the stage for multiple other activities that soon followed. This was the following:

- “Fire Fighter Safety and Emergency Response for Electric Drive and Hybrid Electric Vehicles”: A background research study that assembled core principle and best practice information for emergency responders to assist in their decision making process at emergencies involving electric drive and hybrid e-vehicles. It included a one-day workshop of applicable subject matter experts to review and evaluate the topic.[5]

Certain concepts addressed in this earlier report have been referenced repeatedly. For example, the primary emergency scenarios that could be expected by the fire service responding to an emergency involving an e-vehicle are illustrated in Figure 1, Key Emergency Scenarios for E-Vehicles. This figure considers the four basic possibilities of: (1) Extrication/Rescue; (2) Fire; (3) Water Submersion; and (4) Other Scenarios.

The most probable emergency event involving motor vehicles is a motor vehicle crash (MVC). This could be either a collision with another vehicle, with a stationary object (e.g., telephone pole), a collision between multiple vehicles, or any combination of these. Another possible emergency incident for emergency responders is a vehicle fire. Examples of other emergency scenarios include: a vehicle being partially or fully submerged in water (with or without entrapment); a vehicle draped by downed energized power lines, an external hazardous materials incident exposing the vehicle, or a high angle rescue on the edge of a bridge or cliff.

Figure 1: Key Emergency Scenarios for E-Vehicles.[5]
E-vehicles are generally very similar in appearance to conventional vehicles, and can sometimes not be easily distinguished from them. Arguably the greatest single challenge for the emergency responder to an event involving an e-vehicle is assessment or size-up, which includes adequately identifying the vehicle and the hazards it contains. Size-up effectively provides critical information that informs emergency responders of their next steps. Since vehicles are already full of multiple other hazards, the question asked by emergency responders is “what’s different?” This is summarized in Figure 2: Additional Emergency Responder Concerns for E-Vehicles. In addition to some of the hazards of conventional vehicles such as the air bag deployment system and pressurized tires, this includes: potential electric shock hazard, vehicle movement, and fire extinguishment/overhaul, all within the need to achieve proper assessment and size-up.

**ELECTRIC VEHICLE SAFETY CONFERENCES AND SUMMITS**

Since 2008 there were several conferences and summit/workshops that have been pivotal to addressing key stakeholder concerns and establishing important networking channels. These include the following:

- **"U.S. National Electric Vehicle Safety Standards Summit Summary Report"**: This was a summit held on 21-22 October 2010 in Detroit, Michigan to address safety related codes and standards issues, with a focus on the fundamental codes and standards centric areas of: vehicles, built infrastructure, and emergency responders. The intent was to develop the base elements for an action plan for the safe implementation of e-vehicles using safety standards as the primary mechanism for this action plan.[6]

- **"2nd Annual Electric Vehicle Safety Standards Summit – Summary Report"**: This was a summit held on 27-28 September 2011 in Detroit, Michigan to bring together the appropriate stakeholder groups to further refine a shared implementation plan to ensure that fire and electrical safety standards impacting e-vehicles do not serve as a barrier to their deployment.[7]

- **"Personal Protective Equipment for Hybrid and Electric Vehicles"**: This workshop was held on 1 May 2012 in Quincy, Massachusetts to bring together emergency responders and other stakeholders to develop guiding principles and recommended action steps to address the proper PPE for emergencies involving hybrid or e-vehicles, with a focus on minimizing the risk to emergency responders due to hazards involving electrically energized equipment. This was driven by the vehicle specific emergency response guides from automakers providing conflicting and sometimes contradictory guidance. [8]

- **“Alternative Fuel Vehicle Safety Summit”**: This summit was held on 23 June 2016 in Detroit, Michigan and it reviewed, validated and identified gaps for the operational training materials used by first and second emergency responders and others handling emergencies with alternate fuel vehicles, with an emphasis on gaseous fuels. This includes activities such as: fire events, non-fire emergencies (e.g., submersion), fire investigation, crash reconstruction, tow and savage, extrication practices, refueling and charging infrastructure, etc. [9]

Some key information came from these summits and conferences. This has provided the underpinnings in support of the overall body of knowledge, and similarly enabled important networking to support progressive change. For example, Figure 3: Realms of Focus at the Electric Vehicle Summits, captures in a single illustration the useful concept of key constituent areas as well as codes and standards oversight. This recognizes the three key focus realms of vehicles/batteries,
emergency responders, and built infrastructure. Each of these has its own distinctive characteristics. As further explanation of Figure 3, vehicles and batteries are in the same general orbit, but they are separated since they have different prime drivers and codes and standards oversight. The built infrastructure includes all the supporting activities that provide for and enable the operation of vehicles. Examples include maintenance shops, parts storage warehouses, refuelling facilities, parking garages, and so on. Emergency responders are considered to be all who respond to an emergency event.

Emergency responders are further defined in Figure 4: Emergency Responder Infrastructure. This illustrates the key details of those who are responding to and handling an emergency event. This provides a general framework that clarifies the roles of those involved in this realm.

Specifically, the “Emergency First Responders” are those professionals that are normally the first line of defense for handling the emergency, and who have primary authority at the emergency (i.e., incident command). The “Emergency Second Responders” are those professionals who also get called to the emergency and serve a specific critical function, though they do so under the direction of the responders with incident command.

It’s noted that occasionally the emergency second responders may be the first on the scene of an emergency, for example tow operators who provide roadside assistance. A final group of “Emergency First Receivers” is also included, which effectively is the destination when transport is involved. These are the professionals that ultimately deal with emergency scenarios by providing long-term solutions.

VEHICLE SAFETY RELATED TRAINING

Notable among these various efforts to address standardized operating approaches for emergency responders addressing e-vehicle emergencies, there have been multiple major initiative to develop training materials. This includes several multi-year projects funded by the U.S. Department of Energy. Several of these efforts have been led by the National Fire Protection Association (NFPA) in partnership with a wide range of other interested organizations. More information is available through their special website at: www.evsafetytraining.org.[10]

These programs provide the operational training materials used by first and second emergency responders and others handling emergencies with alternate fuel vehicles. This includes addressing activities such as: fire events, non-fire emergencies (e.g., submersion), fire investigation, crash reconstruction, tow and savage, extrication practices, refuelling and re-charging infrastructure, etc.
Further details of the two primary grant-funded activities are the following:

- "Electric/Hybrid Vehicle Safety Training for Emergency Responders": A training materials development project focused on providing comprehensive awareness and emergency response training for fire fighters and other emergency responders to prepare them for widespread implementation of advanced electric drive vehicles, with objectives to enhance general awareness training and emergency response tactical training, as well as to establish a centralized resource for ongoing technology transfer.[10]

- "Alternative Fuel Vehicle Safety Training Program": Training materials development project focused on providing comprehensive awareness and emergency response training for fire fighters and other emergency responders to prepare them for widespread implementation of alternative fuel vehicles, with objectives to enhance general awareness training and emergency response tactical training, as well as to establish a centralized resource for ongoing technology transfer.[11]

These activities are based on funding from the U.S. Department of Energy (DOE) and thus have generally been centric to the United States. As such, these program target the U.S. fire service, EMS and law enforcement communities (the fire service alone is composed of approximately 1.2 million career and volunteer fire fighters). Hundreds of thousands of emergency responders have now had exposure to this training information. As an example on the breadth of the applicable material, one component is specifically focused on the unique concerns of tow and salvage operators. Another is tailored to the unique needs of the law enforcement investigators. The overall approach provides a complete package of training to address the entire spectrum of safety issues.

ELECTRIC VEHICLE SAFETY RESEARCH

Multiple research projects have been conducted to address various aspects of e-vehicles on today’s roadways. In addition to the reports and proceedings already mentioned are the following research projects of interest:

- "Assessment of Powered Rescue Tool Capabilities with High-Strength Alloys and Composite Materials": A research study that assessed the capabilities and existing field inventory of powered rescue tools and their ability to handle high strength steels found in e-vehicles and other new vehicles now proliferating on the highways.[12]

- "Electrical Vehicle Charging and NFPA Electrical Safety Codes and Standards": A research study that facilitated the safe integration of e-vehicles into the electrical safety infrastructure, by reviewing the technologies likely to impact electrical safety, and presenting an assessment of needed changes to codes and standards along with a roadmap for needed additional research.[13]

The first of these two research studies addresses powered rescue tools that are commonly used by emergency responders to extricate trapped victims from crashed motor vehicles. These tools are relatively heavy duty, and a large inventory exists throughout today’s emergency response community since older tools are typically passed along (i.e., sold second-hand) to neighbouring emergency responder organizations.

Recent years have seen improved auto manufacturing processes to achieve higher fuel efficiencies with lighter weight (yet stronger) vehicles. This has resulted in most of the vehicles on the roadways today using superior high-strength metal alloys and composite materials in their bodies and chassis that are resistant to the older inventory of existing powered rescue tools. In summary, fire fighters have found themselves using what they describe as “work arounds” at emergency extrication events, when they discover their cutting tools are not cutting and their shearing tools are not shearing. Despite the inefficiencies of victim extrication rescue, the good news is that automobile crashes have become much more survivable for passengers in recent years (partly due to these high strength body materials but also due to air bags and other features).

This particular research study on powered rescue tools identifies, collects, and assesses various
informational aspects of this topic involving high-strength metal alloys and composite materials that are challenging the performance of the present generation of powered rescue tools. This includes consideration of vehicle extrication scenarios, clarification on the use of these high-strength materials, review of the existing field inventory of powered rescue tools, and recommendation to address identified knowledge gaps.

The second of these two research projects was conducted to support a task group that administers to the National Electrical Code®, one of the world’s most widely adopted model codes. As thousands and ultimately millions of e-vehicles and their associated charging stations are being continually added to the electrical infrastructure, this is creating influences upon the electrical grid that need to be better understood. For example, what is the impact on the centralized electrical power distribution system when every residence has an e-vehicle charging in their respective garage? What happens during a power failure?

This report presents the results of a project whose overall goal was to facilitate the safe integration of e-vehicles in the electrical safety infrastructure. It provides a review of technologies likely to impact electrical safety and presents an assessment of needed changes to codes and standards and a roadmap for needed research on this topic.

As a result of these two projects and the earlier aforementioned research project (“Fire Fighter Safety and Emergency Response for Electric Drive and Hybrid Electric Vehicles – Final Report”), as well as the multiple conferences and summits, a better understanding has emerged on the needs of the emergency responders for e-vehicle applications. Concerns include issues such as: exposure to products of combustion; electrical conductivity; and the use of extinguishing media for fire control.

These issues and related topics have already been addressed by some limited research conducted by others. The following summarizes several of the more pertinent and applicable studies:

- **Exposure to Products of Combustion:** Exposure to fire by-products is an explicit concern with vehicle fires. The National Institute for Occupational Safety and Health (NIOSH) evaluated chemical and particulate exposures to fire fighters during vehicle fire suppression training. NIOSH is the U.S. federal agency that conducts research and makes recommendations to prevent worker injury and illness. Their research evaluated the exposure hazards from conventional passenger vehicle fires to fire fighters and other emergency responders. Their work underscores the importance of wearing full respiratory and dermal protection when fighting vehicle fires of all types.[14]

- **Electrical Conductivity:** The electrical conductivity of fire hose streams is a well-studied topic. Some technical reports date back to the early 20th century, and are still valid today, recognizing that electricity and hose streams have changed little since their work was conducted. It’s noted that the electrical characteristics of salt water (e.g., for ship board fire fighting) has different electrical conductivity characteristics than fresh water, and requires different consideration.[15]

- **Use of Extinguishing Media:** A research study by DEKRA in Germany clarified the use of water additives for the control and extinguishment of large format lithium ion batteries used in e-vehicles. Full scale fire tests were conducted to evaluate the use of different water additives (e.g., encapsulator agents), as compared to hose streams with fresh water. This research work demonstrated the effectiveness of fresh water for fire fighting and the additional effectiveness of certain water additives.[16]

- **Vehicle Fire Comparison:** A research study by INERIS in France involving full scale vehicle fires is of particular interest because it provided side-by-side comparisons of similar model vehicles. In this case, four vehicles were burned using two pairs of different models of vehicles, with each pair including an e-vehicle and a comparable internal combustion engine vehicle of the same model. Thus the vehicles in each pair were similar other than their propulsion systems. From the perspective of emergency responders responding to a fully involved vehicle fire, the results showed little difference in terms of fire intensity, need for PPE, and concern for projectiles.[17]
• **Full-Scale Electric Vehicle Fire:** Full-scale empirical fire tests in Japan provided a comparison of fire behaviour of an electric drive vehicle versus a comparable internal combustion engine vehicle. Measurements included the total heat release rate of the burning vehicles based on calculations using mass loss rates. In this case, the vehicles were not identical models, thus making a side-by-side comparison difficult. Despite these difficulties, the issues of concern to emergency responders were noted to be similar between the two vehicles.[18]

These and other research studies mentioned above support the body of knowledge that led to a major research effort conducted in 2012 through 2013 to address fire fighter concerns with fighting e-vehicle fires. This is addressed in the next section.

**ELECTRIC VEHICLE FIRE HAZARDS TESTS**

Fires involving cars, trucks, and other highway vehicles are a common concern for emergency responders. Fire service personnel are accustomed to responding to conventional vehicle fires and generally receive training on the hazards associated with various vehicle subsystems. For fires involving e-vehicles, a key question for emergency responders is: “what is different and what tactical adjustments are required?”

A major test project was initiated in 2012 to directly address this question, resulting in a report in the summer of 2013 titled “Emergency Response to Incidents Involving Electric Vehicle Battery Hazards”. [19] This project is part of a larger on-going effort to proactively address the concerns of fire protection professionals and emergency responders.[20] The following provides a summary of this effort:

- "**Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results**": A research study involving full scale fire tests of large format lithium ion e-vehicle batteries to develop the technical basis for emergency response best practices, with consideration for certain details such as suppression methods, PPE, and clean-up/overhaul operations.[19]

The overall goal of this project was to conduct a research program to develop the technical basis for best practices for emergency response procedures for e-vehicles involving large format lithium ion batteries. This included consideration of certain details such as suppression methods, personal protective equipment (PPE), and overhaul/clean-up operations. Basic hazard concerns that were examined during this project included: (a) thermal characteristics, (b) respiratory and dermal exposure, (c) electrical conductivity, and (d) projectiles.

This research work was primarily conducted by Exponent Inc. on behalf of the Fire Protection Research Foundation, with funding from U.S. Dept. of Energy - Idaho National Laboratories, U.S. Dept. of Transportation, and Alliance of Automobile Manufacturers.

A key component of this project was the full-scale testing of large format lithium ion batteries used in these vehicles, with suppression of the vehicle fires by qualified fire fighters. There has been some effort to provide standardized operating approaches for emergency responders fighting fires involving large format lithium ion batteries such as those used in e-vehicles. However, a solid technical basis for these requirements was not well-established at the time of the project.

An applicable emergency operating guidance document of interest at the time of this study was interim guidance provided by the National Highway Traffic Safety Administration (NHTSA), which is a federal agency under the U.S. Department of Transportation. NHTSA stated the following in their Interim Guidance for Electric and Hybrid Electric Vehicles Equipped with High Voltage Batteries: “If the fire involves the lithium ion battery, it will require large, sustained volumes of water for extinguishment. If there is no immediate threat to life or property, consider defensive tactics, and allow the fire to burn out.” [21] Among the questions lingering around this guidance, is the amount of water that equates to “…large sustained volumes...”
Another example of efforts to provide standardized operating approaches for emergency responders fighting vehicular lithium ion battery fires is with the Society of Automotive Engineers (SAE) International. In 2012 they released their document J2990-12, Hybrid and EV First and Second Responder Recommended Practice, which describes the potential consequences associated with hazards from electric drive vehicles and suggests common procedures to help protect emergency responders, tow and/or recovery, storage, repair, and salvage personnel after an incident has occurred with an e-vehicle [22].

Two different styles of batteries were used in these tests from two different vehicle manufacturers. Both styles were based on lithium ion technology and are currently in widespread use in North America. These battery styles were designated for this project as Battery A and Battery B. Seven large format lithium ion batteries were tested, with three Battery A type batteries and four Battery B type. Battery A had a 4.4 kWh electrical storage capacity that is normally installed under the rear cargo compartment of the vehicle. Battery B was a 16.0 kWh battery normally installed under the vehicle floor pan spanning nearly the entire length of the vehicle, from the rear axle to the front axle in a T-shaped configuration. These batteries were all tested under fire conditions at a 100 percent state of charge.

Prior to the manual suppression tests, a single 16.0 kWh battery (Battery B) was burned in a full-scale heat release rate (HRR) test at Southwest Research Institute (SwRI) in San Antonio, Texas. This was conducted with full measurement and without any fire fighting intervention, to clarify free burning characteristics and confirm the ignition scenario to be used in the subsequent test series.

Six large format batteries were used for the manual suppression tests. These were conducted in two sets of three batteries each. The tests were conducted at the Maryland Fire and Rescue Institute (MFRI) in College Park, Maryland. MFRI is the fire service training academy for the State of Maryland, which satisfied one of the project requirements to conduct the tests at a nationally recognized fire service training site.

These six batteries were each installed within a generic vehicle fire trainer “prop” (a.k.a., the “mule”) that was intended to replicate an actual e-vehicle. Figure 5 provides an illustration of the vehicle used in the MFRI test series. Each test also included manual fire suppression involving fire fighters with fresh water hose streams.

All manual suppression tests subjected the batteries to simulated exposure fires originating underneath the vehicle chassis using gas burners that could be remotely controlled. The tests were conducted without opening, altering, or manipulating any of the internal features of the large format batteries. An external ignition source was chosen using four propane fuelled burners that could be remotely controlled to replicate a realistic flammable liquid pool fire beneath the e-vehicle.

The manual suppression tests were conducted with and without vehicle interior finishes. All fire suppression activities were conducted by qualified active duty fire fighters, with no special instructions provided other than to fight the fire according to their normal tactical operations and procedures. Only fresh water was used, i.e., not salt water or the use of any water additives.

The following is a summary of the overall observations from the manual suppression tests:

- **Electrical Conductivity:** No adverse electrical conditions were noted. Test data indicated that the chassis and nozzle current and voltage levels were negligible. All batteries were tested at 100 percent state of charge.
• **Projectiles:** No projectiles were observed from the battery pack in any of the tests. None of the batteries tested “burst” or “exploded” in any manner. However, in all tests “popping” and “arching” sounds and off gassing of white smoke consistent with internal battery cells from the battery pack undergoing thermal runaway were recorded.

• **Water Extinguishment:** Water was used to successfully extinguish all fires during the suppression tests; however, the amount of time required applying water and the total volume of water necessary for extinguishment was significantly larger than what is typically required for extinguishing a traditional internal combustion engine vehicle fire.

• **Heat Flux:** The heat flux was comparable to what would be expected for a conventional internal combustion engine vehicle. Fire tests involving vehicle interior finishes produced significantly more intense fires than battery only fires.

• **Overhaul and Stranded Energy:** In one test, the battery reignited 22 hours after the battery was fully extinguished and the test concluded, and with the fire deemed to be "out" in accordance with available measurement techniques and observations. Once this test had been completed, this battery showed no signs of visible flaming, no signs of significant off gassing or smoking, and surface temperature readings on the battery were approximately ambient (as determined using an infrared camera). Following each individual fire test the subject battery was isolated on a remote concrete pad for extended monitoring. The re-ignition was attributed to the stranded electrical energy, and for all batteries there was no way to measure remaining electrical energy due to the fire damage to the battery.

In general, from the perspective of fire fighters and other emergency responders, a fire involving an e-vehicle with a large format lithium ion battery is comparable to a fire involving an internal combustion engine vehicle. A common question asked by fire fighters is what is different with an e-vehicle fire (with large format lithium ion batteries) versus a conventional vehicle fire? The answer from these tests: they are relatively similar but require certain tactical adjustments.

![Figure 6: Test B3, with ignition (top left), off-gassing (top right), fully involved (bottom left), burners off (bottom right).][19]

Specifically, the differences with basic hazards involves consideration of the following four characteristics: (a) thermal characteristics, (b) respiratory and dermal exposure, (c) electrical
conductivity, and (d) projectiles. The tests showed that thermal concerns have attributes requiring certain additional consideration to address fire duration (but not intensity), while the other three characteristics are similar to conventional vehicles. For example, the need for PPE to protect against respiratory and dermal exposure was deemed to be minimally different than a conventional vehicle, requiring full PPE protection. Likewise, there were no projectile hazards that met or exceeded what is already seen from regular vehicle fires due to the sudden release of energy from tires, shocks, or airbag deployment systems. Prior to the tests the stray electrical energy was a question, though the study results indicated no adverse measurements of concern, including at the hose line nozzles during fire fighting operations.

The thermal characteristics was the one subject area with an identifiable difference between e-vehicle fire fighting and internal combustion engine vehicles. The fires were arguably similar in terms of overall HRR, temperatures, and other general parameters, but the one noteworthy difference was that the fires were difficult to suppress and extinguish from a time duration standpoint. They continued for longer periods of time and therefore required more water to complete the fire fighting task.

The fires are not necessarily more intense, though they tend to burn longer and can be difficult to access with a hose stream. One tactical adjustment involves not manually breaching or penetrating the high energy electrical battery during fire fighting (e.g., with a pike pole or haligan bar), and being cautious and respectful of the possible stranded electrical energy in the large format battery. Thus the fires are more difficult to fully extinguish and require more water. Otherwise the fire fighting tactics with fresh water are generally the same. As a result, an aspect requiring special consideration is overhaul, and dealing with damaged batteries that may include stranded electrical energy.

It was mentioned earlier that a detail of particular interest is the volume of water required to control and extinguish the fire. This relates back to already established guidance information, which simply indicates that copious amounts of water are required for extinguishment. Thus it is helpful to examine the amount of fresh water used in these tests. Table 1 summarizes the duration of the fire fighter use of hose streams and the volume of water used.

The degree of variability of the results in Table 1 is partially attributed to different fire fighting crews. Interestingly, the fire tests with interior components (A3 and B3) produced significantly more intense fires and appeared to more completely consume the large format batteries, resulting in less stranded electrical energy and arguably more rapid fire extinguishment.

Importantly, the amount of water required for these fires in some cases exceeds what is normally carried on modern fire apparatus, and thus fire fighters responding to e-vehicle fires in remote locations with limited water supply will need to consider alternatives. For example, in fire emergencies such as those with no exposures in remote areas, the alternative of letting a fully involved large format lithium ion battery burn may be a viable option, especially with regard to the challenges of overhaul and addressing batteries with stranded electrical energy.

<table>
<thead>
<tr>
<th>Test</th>
<th>Fuel Load</th>
<th>Suppression Time (minutes)</th>
<th>Water Flow Time (minutes)</th>
<th>Total Water Flow (liters (gallons))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Battery only</td>
<td>5:88</td>
<td>2:20</td>
<td>1,041 (275 gal)</td>
</tr>
<tr>
<td>A2</td>
<td>Battery only</td>
<td>36:60</td>
<td>3:53</td>
<td>1,673 (442 gal)</td>
</tr>
<tr>
<td>A3</td>
<td>Battery &amp; interior components</td>
<td>49:67</td>
<td>9:77</td>
<td>4,013 (1060 gal)</td>
</tr>
<tr>
<td>B1</td>
<td>Battery only</td>
<td>26:52</td>
<td>14:03</td>
<td>6,640 (1754 gal)</td>
</tr>
<tr>
<td>B2</td>
<td>Battery only</td>
<td>37:60</td>
<td>21:37</td>
<td>9,990 (2639 gal)</td>
</tr>
<tr>
<td>B3</td>
<td>Battery &amp; interior components</td>
<td>13:88</td>
<td>9:32</td>
<td>4,410 (1165 gal)</td>
</tr>
<tr>
<td>B4</td>
<td>Free burn to measure HRR, etc.</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
In summary, due to the prolonged nature of fires involving large format lithium ion batteries, one aspect of fighting these fires that requires additional focus is overhaul and post-fire handling of the vehicle. The batteries likely will have some level of stranded electrical energy, and the phenomenon of re-ignition is a genuine concern. This is particularly challenging when it is no longer possible to measure the electrical energy within the battery due to the damage from the fire. In all cases, the vehicle and battery manufacturers should be consulted for the proper protocol and special directions for handling damaged batteries that may include stranded electrical energy. Fire damaged batteries should be isolated in a fire safe area after a fire until all stranded electrical energy is deemed to no longer be a concern.

**LITHIUM ION BATTERY ASSESSMENTS**

Another aspect of the e-vehicle roll-out and popularity of lithium ion batteries is bulk storage and transport of these batteries. There has been a rising concern on the handling of bulk batteries, and a particular concern is a thermal runaway event occurring during transport. A noteworthy example in this regard are the restrictions on the transport of lithium ion batteries on-board aircraft [23].

During storage and shipment, new batteries are normally handled and conveyed at a 50 percent state of charge. In addition to this stored electrical energy, there is already an appreciable fuel load with most of these batteries due to plastic casings and other components. This includes small and large format batteries alike. While this may not present an exceptional concern with single small format batteries (e.g., hand held power tools) by themselves, this is not the case once stored in bulk.

Multiple research projects have been conducted to address this aspect for the fire protection for lithium ion batteries. Specifically, the following two project reports are of interest:

- **"Lithium Ion Batteries Hazard and Use Assessment"**: A research study to develop the technical basis for requirements in codes and standards to support the protection requirements for hazards involving lithium ion batteries. This report provides a literature review of battery technology, failure modes and events, usage, codes and standards, and a hazard assessment during the life cycle of storage and distribution. It additionally provides a research approach toward evaluating appropriate facility fire protection strategies for the bulk storage of lithium ion batteries.[24]

- **"Lithium Ion Batteries Hazard and Use Assessment Ph. IIB"**: A research study that provides results of full scale empirical fire tests of high rack storage of common lithium ion batteries, to clarify their flammability characteristics as compared to standard commodities in rack storage. This addressed various sizes of lithium ion batteries, including batteries for electronic devices such as laptops, power tools, cameras, and cell phones.[25]

The principal stakeholder group pushing for further research on behalf of these two FPRF projects has been the property insurers, partly due to their concern on how best to provide built-in fire protection measures for batteries stored in bulk in large warehouses. Serious questions exists if conventional fire protection system designs are capable of handling these battery storage applications.

The first of these two reports is effectively a Phase I effort and provides a review of the hazards associated with lithium ion battery storage, with an aim of developing fire protection strategies to mitigate loss associated with fire incidence with these batteries in bulk storage and distribution, alone and in manufactured products. As e-vehicles continue in their popularity in the marketplace, there is an expectation of a step increase in the number and size of battery packs in storage and use.

The overall aim of this first project was to develop the technical basis for requirements in NFPA and other standards which prescribe protection requirements. The report provides a literature review of battery technology, failure modes and events, usage, codes and standards, and a hazard assessment during the life cycle of storage and distribution. It lays out a research approach toward evaluating appropriate facility fire protection strategies.

The second of these two projects is the more robust Phase IIB effort that includes full-scale fire tests.
This builds on the Phase I study and addresses lithium ion battery cells and small battery packs (8 to 10 cells) that are in wide consumer use. These tests are noteworthy since they involved full scale testing of pallet loads of batteries to determine optimum fire sprinkler protection. The report presents the results of Phase II which is a comparative flammability characterization of common lithium ion batteries to standard commodities in storage.

ENERGY STORAGE SYSTEMS

Yet another trans-dimensional use of lithium ion batteries is for electrical energy storage systems, also referred to as ESS. This includes re-purposed large-format e-vehicle batteries that are grouped together to provide bulk energy storage. These sometimes involve e-vehicle and other batteries in second life applications.

There is an increasing demand for the implementation of ESS technology. Some of these systems are relatively sophisticated designs, while others are more simplistic (e.g., re-purposed large format e-vehicle batteries stored in the equivalent of a shipping container). The high demand for ESS is primarily due to ‘peak shaving’, to store electrical energy during low-demand periods (e.g., at nighttime) for use during high demand periods (e.g., during the day-time).

The Foundation has conducted a workshop and a separate research report on this topic area, primarily with a focus of clarifying the hazard. The applicable reports are:

- “Workshop on Energy Storage Systems and the Built Environment”: The Research Foundation coordinated with the Fire Department of New York City (FDNY) to host a workshop on 19 November 2015 with all stakeholders to discuss the installation of electrical Energy Storage Systems (ESS) using technologies such as bulk lithium ion batteries and flow batteries, especially in residential occupancies from high-rise buildings to single- and multi-family homes. The purpose was to clarify the potential hazard, review recommended built-in fire protection measures, and inform fire fighting practices. [26]
- “Hazard Assessment of Lithium Ion Battery Energy Storage Systems”: This project develops a hazard assessment to address the usage of lithium ion batteries in energy storage systems (ESS), to allow for the development of safe installation requirements and appropriate emergency response tactics. [27]

A key driving factor for ESS is the green movement and the need to promote clean renewable sources of electricity, such as the use of photovoltaics or wind turbines. This requires that the electrical energy be stored for use when the generation capacity is limited, which occurs regularly for these systems (e.g., photovoltaics, at night).

The specific need for the workshop was based on proposed installations of ESS throughout large cities. In particular, the City of New York has numerous proposed installations, some of which are on upper floors of high rise buildings. Local Authorities Having Jurisdictions and emergency responders, along with ESS integrators, installers, insurers and others, are challenged by the lack of clear direction on the overall hazard and optimum approaches to address the hazard, including appropriate built-in fire protection measures and emergency responder strategies and tactics. The research report soon followed, and this provides a comprehensive hazard assessment of the ESS technology. It also provides guidance on the use of built-in fire protection systems and the approach required for fire fighting efforts if an emergency event were to occur.

CHALLENGES AND OPPORTUNITIES AHEAD

Multiple research projects and consensus-building networking conferences have been conducted as e-vehicles have proliferated, and this has helped stay ahead of adverse events in a proactive rather than reactive manner. As technology evolves, it is introducing a future with new challenges as well as new solutions.

A looming technical challenge that requires attention is stranded electrical energy in damaged batteries. This phenomenon is relatively unique in fire protection engineering, with supposedly
extinguished batteries coming back to life much later after the event has been normally considered “closed” and “extinguished”. In the MFRI tests, a damaged fully charged large format vehicle battery re-ignited on an isolated concrete holding pad 22 hours after the completion of the fire test, and after being declared officially “out” from a fire fighting standpoint.[29] Thus, isolation of a post-fire damaged battery, which can potentially re-ignite, is a relatively new requirement for emergency responders dealing with e-vehicle fires. This is in addition to the obvious electrocution hazard.

This aforementioned research has focused on specific large format lithium ion batteries, and further testing of additional battery configurations and technologies is warranted. Of particular interest are new battery technologies like the lithium metal polymer (LMP) batteries in production in Europe, that have dramatically different burning characteristics than the large format lithium ion batteries in production for vehicles in North America. Also of interest and requiring further study are massless battery designs, where the battery is inherently a part of the vehicle body for weight efficiency. All new battery chemistries and geometries that burn in a hazardous manner, need further evaluation.

Fresh water is the basic staple of the fire service for manual fire fighting operations, but the use of water additives to improve effectiveness, or the use of other than fresh fire fighting water (i.e., the use of ocean or salt water), are topic-areas that requires further study. Some of the water additives show promise in terms of positive extinguishing characteristics, and additional credible, scientifically-based research is needed to support their use.[28]

The future is bright for the vehicular and transportation industry. Some of the technological innovations that are introducing new hazards are also yielding safety improvements. An example mentioned earlier is the new high-strength light-weight alloy vehicle bodies. Although this is posing challenges for emergency responders, it is something they can deal with once aware of the problem, and in the meantime passenger protection in vehicle crashes has seen noteworthy improvements.

Vehicle telematics and vehicle data recordings present a great opportunity for emergency responders. Vehicle size-up is a critical initial task at every emergency event. Today this can be very challenging for emergency responders confronting heavily damaged vehicles, and dealing with an unknown hazard significantly increases their risk as they perform their duties. A clear solution would be the enabling of electronic-badging using RFID or similar technology. This holds genuine promise for emergency responders who need real-time data during an emergency. Further, this applies for post-event applications. Clarification of recommended protocols are needed for investigators who need to re-power damaged vehicles to safely recover vehicle data.

As e-vehicles and their related technologies continue to evolve and the fruits of their intended purpose flourish, society must continue to be vigilant for possible hazards, wise enough to understand the implications of failure, and courageous enough to be proactive stewards in the name of safety.

REFERENCES
15) Sprague C. S., “Electrical Conductivity of Fire Streams”, Research Series #53, Engineering Experiment Station, Purdue University, Lafayette IN, Jan 1936.
23) Federal Aviation Administration, “Pack Safe; spare uninstalled lithium ion and lithium metal batteries”, website: https://www.faa.gov/about/initiatives/hazmat_safety/more_info/?hazmat=7; accessed 30 June 2016.
New International Standard for Fire Suppression Systems in Buses and Coaches

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ABSTRACT

Fires in buses are a common and global problem. About 2/3 of all bus fires start in the engine compartment of the bus. This has naturally led to efforts of reducing the fire risk of bus engine compartments. A common way to limit the extent and consequences of bus fires is to install automatic fire suppression systems in the engine compartment of the buses. SP Fire Research has developed a method to test and evaluate such systems under standardized and realistic conditions. An amendment of UNECE Regulation 107 has made fire suppression systems to become mandatory on buses in many European countries with test requirements mainly based on SP Method 4912. The amendment will likely improve the fire safety of buses in Europe substantially. Standards for fire suppression systems are also progressing in other countries and regions.

KEYWORDS: Fire suppression systems, buses and coaches, SP Method 4912, UNECE Regulation 107, fire safety standards

INTRODUCTION

Fires in buses are common and buses are daily involved in fire incidents. For instance, in the US approximately six school bus fires are reported every day [1]. Recent statistics from Sweden show that at least 0.76 percent of all buses in service annually will suffer from an incident with fire or smoke [2]. This is confirmed by surveys made in Germany where between 0.5 and 1 percent of all buses suffer from a fire incident every year which corresponds to at least 350 – 400 fires annually [3]. From time to time bus fires result in numerous fatalities. An example is a fire in October 2015 in Puisseguin, France, where a bus crashed into a truck, causing the two vehicles to burn and the death of 43 people. Luckily most fire incidents do not lead to fatalities, but the property loss and the cost due to business discontinuity, rescue operation and traffic jam can be extensive.

About 2/3 of all bus fires start in the engine compartments of the buses [2]. This has naturally led to efforts of reducing the fire risks of bus engine compartments. A way of increasing the fire protection, which has become more and more common, is to install an automatic fire suppression system in the engine compartment. Such systems consist of one or more containers of suppression agent and a fire detection and activation system that releases the suppression agent in the event of fire. A piping or tubing system is often used for the distribution of the suppression agent from the container to the different areas of the engine bay. Some systems, e.g. with aerosol generators, often have generators installed in the engine room and releases the agent directly from the generator. In addition to suppressing the fire, the systems are normally also designed to warn the bus driver through an alarm in case of fire. Various types of suppression agents are used including different sorts of dry chemical, water mist, foam, aerosol, gaseous agents or sometimes combinations of those.

The installation of automatic fire detection and suppression system for buses has been recommended
by fire researchers, trade associations, accident investigators and transport authorities [3], [4], [5], [6]. It is generally not perceived as the ultimate solution on the bus fire problem, but as one of several tools necessary to limit the extent and the consequences of bus fires occurring in society. For instance, a document addressed to the Working Party on General Safety Provisions (GRSG) of the United Nations Economic Commission for Europe (UNECE), jointly submitted by the transport authorities of France, Germany, Norway and Sweden in 2010 emphasizes that installation of automatic fire suppression systems in bus engine compartments should be prioritized among other actions for improving bus fire safety [7].

Fire suppression systems for buses have traditionally been tested and verified according to general standards for suppression systems with different test protocols depending on the agent used. This has made it difficult to compare the suppression performance of different types of agents and systems with a combination of agents have not always been able to approve as a whole. The tests have not either taken into account the specific challenges with the application, in this case engine compartments of buses.

An approach to validate suppression system performance with focus on the application has been to carry out suppression tests in the engine compartment of a bus. This type of testing has been used e.g. by bus manufacturers to evaluate different suppression system solutions. One example of such test procedure is described in the standard SBF 128 published by the Swedish Fire Protection Association [8]. The test is performed while the engine is on idle and the fire load, mainly consisting of sawdust soaked in diesel and gasoline, are being spread in the engine compartment, ignited and allowed to burn for 20 seconds before activation of the fire suppression system. A passed test approves the system for installation in any type of bus given that it also fulfils a set of other requirements, for example a fixed minimum amount of suppression agent depending on the agent type. This has been required by Swedish insurance companies in their request for fire suppression systems on all insured buses since 2004. However, in a forthcoming edition (SBF 128:3) the engine compartment suppression test is planned to be replaced from 2017 by the standardized mock-up test procedure described in this paper.

Several fire suppression system manufacturers have designed their own tests to develop and optimize suppression systems and to demonstrate the performance, e.g. Kidde has published an article on development of a test method for fire suppression systems for buses [9].

During recent years, some major research initiatives have been taken to develop standardized tests for engine compartment fires. Southwest Research Institute (SwRI) was contracted with The National Highway Traffic Safety Administration (NHTSA) to develop test apparatuses and test procedures to evaluate candidate fire detection and suppression systems for motorcoach engine compartments [10]. FM Global’s Research Division has developed FM Approval Standard 5970 Protection Systems for Heavy Duty Mobile Equipment. Though focusing on heavy duty equipment rather than buses, the applications have much in common and thus worth mentioning here. [11]

This paper concentrates – mainly from a European perspective – on the development of a test method and new legislation of fire suppression systems for buses with test requirements derived from this method. In this paper the word bus comprehends buses and coaches unless specified.

DEVELOPMENT OF TEST METHOD

Despite the growing demand for fire suppression systems for buses and recent year’s research efforts there were previously no existing international standards for testing and validating such systems. Based on earlier research on bus fire safety, SP initiated a project in 2010, supported by the Swedish Transport Agency, with the purpose of developing a test standard for evaluating automatic fire suppression systems meant for bus engine compartments [12]. The purpose was to design a standardized test setup which allows systems with any type of suppression agent or combination of
agents to be tested against the same fire hazards under realistic conditions and thus facilitate comparison of the performance of different agents and suppression system solutions. The main goal was to develop a test method that possibly could be implemented in the UNECE Regulation No 107. In cooperation with a broad reference group a comprehensive work started which included both theoretical and practical studies. Different models of buses were reviewed, paying special attention their aerodynamic, geometrical and thermodynamic aspects, as well as the properties of the flammable materials contained in these compartments. Full scale fire tests were conducted using commercial buses with operating engines and more than 450 laboratory fire suppression tests were performed with different suppression system types in order to develop the test methodology. Under its development, careful attention was paid to the identification of test conditions which would represent realistic fire scenarios. This work led to the test method SP Method 4912, Method for testing the suppression performance of fire suppression systems installed in engine compartments of buses and coaches [13], [14].

Figure 1  Fire suppression testing according to the described method. A fan is seen to the left.

The fire suppression tests are performed in a test apparatus which is a full scale engine compartment mock-up with obstructions, aiming to represent generally cluttered engine compartment interior. The external gross volume of the test rig is 4 m$^3$. Figure 1 shows a fire test according to the method.

The method includes eleven different suppression tests which differ from each other with respect to fire source type, severity and location, grade of obstruction and number of the fire sources used, as well as air flow rate applied, see Table 1.

The test report rates the tested suppression system based on the number of passed (extinguished) tests and the ability to protect against hot surface re-ignition. This means that manufacturers can compete with each other by improving their systems to increase the number of passed tests. It also allows e.g. purchasers to set stricter requirements, e.g. passing certain types of tests, for buses frequently utilized in special hazard areas, such as tunnels and underground car parks for example.
Table 1  Tests in SP Method 4912

<table>
<thead>
<tr>
<th>Test</th>
<th>Air flow rate</th>
<th>Scenario category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 m³/s</td>
<td>High fire load test</td>
</tr>
<tr>
<td>2</td>
<td>0 m³/s</td>
<td>Low fire load test</td>
</tr>
<tr>
<td>3</td>
<td>0 m³/s</td>
<td>Hidden fire test</td>
</tr>
<tr>
<td>4</td>
<td>0.5 m³/s</td>
<td>Class A-fire test</td>
</tr>
<tr>
<td>5</td>
<td>1.5 m³/s</td>
<td>High fire load test</td>
</tr>
<tr>
<td>6</td>
<td>1.5 m³/s</td>
<td>Low fire load test</td>
</tr>
<tr>
<td>7</td>
<td>1.5 m³/s</td>
<td>Hidden fire test</td>
</tr>
<tr>
<td>8</td>
<td>3 m³/s</td>
<td>High fire load test</td>
</tr>
<tr>
<td>9</td>
<td>3 m³/s</td>
<td>Low fire load test</td>
</tr>
<tr>
<td>10</td>
<td>3 m³/s</td>
<td>Hidden fire test</td>
</tr>
<tr>
<td>11</td>
<td>0 m³/s</td>
<td>Re-ignition test</td>
</tr>
</tbody>
</table>

Since the method focuses on suppression performance SP started a project in 2013 in order to complement with a method for testing detection capability, called SP Method 5320, which currently is getting finalized [15]. In parallel SP has established a voluntary certification and quality mark for fire suppression systems for buses and coaches – SPCR 183 (SP Certification Rules 183) with a set of other requirements on the system e.g. durability related tests [16].

UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE (UNECE)

The UNECE World Forum for Harmonization of Vehicle Regulations (WP.29) is a unique worldwide regulatory forum within the institutional framework of the UNECE Inland Transport Committee. The first UN Agreement, adopted in 1958 provide the legal framework allowing Contracting Parties (member countries) attending the WP.29 sessions to establish regulations concerning motor vehicles and motor vehicle equipment for UN Regulations, annexed to the 1958 Agreement.

UN Regulations contain provisions for vehicles, their systems, parts and equipment related to safety and environmental aspects. They include performance-oriented test requirements, as well as administrative procedures. The latter address e.g. the type approval of vehicle systems, parts and equipment and the mutual recognition of the type approvals granted by Contracting Parties. [17]

The Working Party on General Safety (GRSG) is a subsidiary body of WP.29 that prepares regulatory proposals on general safety to WP.29. This group of experts conducts research and analysis to develop general safety requirements for vehicles, in particular buses and coaches. Final decisions are taken by Government representatives by vote at the World Forum WP.29 level. [18]

UNECE Regulation 107

There are several UNECE regulations with requirements relevant for fire safety of vehicles. One of them, Regulation No. 107 [19], covers a wide range of topics for buses, many related to fire safety. The main fire related requirements are:

- No flammable or liquid-absorbing sound-proofing materials in engine compartment are allowed.
- Heat-resistant partitioning between engine compartment (or any heat source) and rest of the bus.
- Safe construction and installation of cables.
- Fusing.
- Isolating switch for circuits with a voltage exceeding 100 V.
- Safe and accessible installation of the battery.
- Space provided for fire extinguishers and first-aid kits.
- No flammable materials within 10 cm of any potential heat source, such as exhaust systems or high voltage equipment for example.
- Alarm systems detecting excess temperature in the engine and combustion heater compartment (if the engine compartment is located to the rear of the driver). Alarm systems detecting either smoke or excess temperature shall also be installed in toilet compartments; driver’s sleeping compartments, and other separate compartments.

In 2015 GRSG decided that automatic fire suppression systems will be required on buses with more than 22 passengers of class I, II and III. WP.29 subsequently stated formally the decisions taken by GRSG [20]. Class I means buses with area for standing passengers while class II are buses constructed principally for the carriage of seated passengers but allow carriage of standing passengers in the gangway. Class III means buses constructed exclusively for the carriage of seated passengers. Class I and II corresponds (roughly) to city buses and class III to coaches. The requirement applies to buses that have a combustion engine or a combustion heater located to the rear of the driver. The buses shall be equipped with a fire suppression system in the engine compartment and in the combustion heater compartment if such exists.

For an UNECE type approval according to Regulation 107 the requirement becomes mandatory for Class III-buses from July 2018 for new vehicle types and from July 2019 for new vehicles. For Class I and II the requirement become mandatory for new vehicle types from September 2020 and September 2021 for new vehicles (tentative). Table 2 shows an overview of the dates.

<table>
<thead>
<tr>
<th>Vehicle class concerned</th>
<th>UNECE R107 type approval with regard to fire suppression system becomes possible</th>
<th>Fire suppression system becomes mandatory for UNECE R107 type approval of new vehicle types</th>
<th>Fire suppression system becomes mandatory for UNECE R107 type approval of new vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I and II (&quot;city buses&quot;)</td>
<td>October 8, 2016 (tentative)</td>
<td>September 1, 2020 (tentative, new vehicle types)</td>
<td>September 1, 2021 (tentative, new vehicles)</td>
</tr>
<tr>
<td>Class III (&quot;coaches&quot;)</td>
<td>June 18, 2016</td>
<td>July 11, 2018 (new vehicle types)</td>
<td>July 11, 2019 (new vehicles)</td>
</tr>
</tbody>
</table>

Members States of Regulation 107

Regulation 107 is signed by 45 member states shown in Table 3, so-called Contracting Parties. Those contain not only members of the European Union but also countries such as Russia, Turkey, Kazakhstan, Egypt, Tunisia, and Malaysia [21].
Table 3  Countries that has signed Regulation 107

<table>
<thead>
<tr>
<th>Country</th>
<th>Country</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albania</td>
<td>Georgia</td>
<td>Portugal</td>
</tr>
<tr>
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Content of the new requirement in Regulation 107

Regulation 107 gives two alternative ways to test and approve a fire suppression system [22]: In order for the system to be approved for installation in any bus or coach (general approval) it needs to be tested in the standardized test mock-up previously described. As an alternative, it can be tested in the engine and combustion heater compartment of the specific bus model where it is going to be installed.

The test that gives the general approval includes four tests extracted from SP Method 4912 (test numbers are referring to Table 2):

- High fire load test (test 1). The test includes a small fuel spray, pool fires and fires in fibrous material. The test is performed without air flow and with the suppression system cooled down to minimum operating temperature
- High fire load with forced air flow of 1.5 m$^3$/s (test 5). The test includes a large fuel spray, pool fires and fires in fibrous material (at other locations than in test 1)
- Low fire load test with forced air flow of 1.5 m$^3$/s (test 6). The test includes small pool fires at different locations
- Re-ignition test (test 11) with oil dripping onto a hot surface heated to 600 °C

In order for an approval, all fires must be extinguished. The re-ignition test is passed if re-ignition is prevented during a minimum of 45 seconds. The system needs to have the same setup (nozzle location etc.) during all tests. For larger or smaller engine compartments the regulation includes a set of scaling rules.
In addition to the fire testing a fully documented fire hazard identification analysis is to be performed for every vehicle type where a fire suppression system is to be installed in order to adapt the system to the bus model. The analysis shall be conducted prior to the installation in order to determine the location and direction of the suppression agent discharge points (e.g. nozzles). Potential fire hazards within the engine and combustion heater compartment shall be identified and the discharge points located such that the suppression agent will be distributed to cover the fire hazard when the system activates. The spray pattern and direction of discharge points as well as the discharge distance shall be ensured to cover identified fire hazards. The system shall also be ensured to work properly regardless of the vehicle’s altitude.

The fire hazard analysis shall, as a minimum, take into account the following components:

(a) those whose surface may reach temperatures above the auto-ignition temperature for fluids, gases or substances that are present within the compartment,
(b) electrical components and cables with a current or voltage high enough for an ignition to occur,
(c) hoses and containers with flammable liquid or gas (in particular if they are pressurized).

Conducting testing by the alternative method, the approval will only be valid for that specific bus model and similar models which do not differ in the following essential aspects:

(a) The position of the engine compartment
(b) Maximum gross volume
(c) General layout of components in the compartment (i.e. position of the determined fire hazards)

The same four fire scenarios are to be performed and the test conditions needs be adapted for the intended engine and combustion heater compartment. The regulation states that the adaption shall provide an equivalent level of safety with the principles of adaption being verified by the Technical Service (i.e. test inspector) responsible for the testing. The adaptation shall be based on determining the location of the fire hazards within the compartments. In order to facilitate the positioning of the fire trays in the compartments additional supports may be used and the height of the prescribed test fires may be lowered to a minimum of 40 mm.

Regulation 107 requires fire alarm systems but does not include any test criteria for validating the detection capability of fire detectors.
OTHER COUNTRIES AND REGIONS

Fire safety standards are also progressing in other countries and regions.

India

The Automotive Industry Standards Committee of India (AISC), constituted by the Indian Government, decided in 2015 to formulate an AIS standard on the subject “Fire Detection & Suppression System (FDSS) for Buses” (AIS-135). The aim was to standardize the specifications and test procedures for FDSS systems with technology neutral requirements covering only performance parameters and not supplier specific specifications. The committee notes that a significant majority of the bus fire accidents on Indian roads originate from the engine bay of the vehicle. The committee expresses a sense of urgency due to the requirements for fire suppression systems that already are included in the governmental “Urban Bus Specification II” (UBS-II) from 2014. Financial assistance for the procurement of city buses is provided from the government if the specifications are followed.

In July 2016 a “finalized draft” of the forthcoming standard AIS-135 was released. Buses required having fire detection and suppression systems (e.g. according to UBS-II) shall comply with the requirements of the standard. The work is almost identical to the fire suppression system requirements in UNECE Regulation 107 and includes the same mock-up testing for general approval with requirement on fire hazard analysis and gives the option of performing the testing in a bus engine compartment. However, unlike Regulation 107 it also includes a testing procedure where the detection system must show that it gives an alarm when affected by a fire. AIS-135 specifies that the requirements of the standard not are applicable to Electric powertrain vehicles (EVs). [23]

Israel

As the first country in the world the Israeli Ministry of Transportation decided in 2013 to require fire suppression systems on all the country’s buses, as part of a package to improve safety on buses. The fire suppression tests required in Israeli standard I.S. 6278 are to be performed in the SP Method 4912 mock-up. Requirements are also derived from the Swedish Fire Protection Association guideline SBF 128 and the Australian Standard AS 5062:2006. [24]

South Africa

The South African Bureau of Standardization has put together a working group for developing a SABS standard for buses and heavy vehicles. There are discussions about basing the requirements on Regulation 107.

South America

Fire suppression systems are legislated in Chile with test requirements according to SBF 128:2, which include fire suppression testing in the engine compartment of a bus. The law was said to apply from December 2013 but after complaints from bus companies and trade unions the requirement was postponed one year and has been compulsory from 2014.

Peru has been working on a new regulation for fire suppression systems. There are ongoing discussions if the standard should follow SBF 128 or certified systems according to SPCR 183.
Transit authorities

New procurement specifications is usually a much faster way getting improved safety than through changed legislation. In several places, especially within US and Australia, transit authorities are increasingly prescribing fire suppression systems in their procurement documents. One example of this is Sydney metro and outer metro areas where approximately 2,400 buses were going to be retrofitted. The governmental Transport for New South Wales (TfNSW) sent out a Request for Proposal in April 2016 where the procurement specifies that the system must be tested according to SP Method 4912 and certified according to SPCR 183 or an equivalent recognized certification, design and testing process. Furthermore, as required by SPCR 183, the Supplier must undertake a design risk assessment process for each Bus Type in collaboration with the Contract Bus OEM supplier, the Contract Bus owner and TfNSW.

DISCUSSION

Through the new requirements on automatic fire suppression systems in UNECE Regulation 107, it is likely to expect that the fire safety of buses will be improved substantially. The improvement is not just due to the presence of fire suppression systems because such systems are already used to large extent, but also that the quality of the design and installation is expected to be enhanced since the design of the system including the fire hazard identification will be incorporated in the bus manufacturing process and the installation performed in factory rather than through retrofit after the deliverance of the bus. With the bus manufacturer taking a greater overall responsibility for the fire safety including the fire suppression systems will almost certainly lead to more integrated and smarter solutions.

It will be important to continuously follow-up the function of suppression systems in fire incidents so that data of the system performance can be achieved and both systems and fire standards continuously being improved. This is especially important considering new and alternative fuels gaining ground, where there currently are less available data and statistics on fire incidents.

An important step that needs to be taken to continue the work forward is to improve the requirements on fire detection capability for engine compartments. Unless the detection side of the automatic fire suppression system works properly, the suppression agent might not be released as it should and the overall performance of the system impaired. Hopefully Regulation 107 within short can be complemented with a relevant and well-taught test protocol for fire detectors.

REFERENCES

5. Slutrapport RO 2013:01, "Brand med två biogasbussar i stadstrafik i Helsingborg, Skåne län, den 14 februari 2012”, Dnr O-03/12, Stockholm, Sweden, 2013
7. Informal document No. GRSG-98-08: “Fire Safety: Priorities of the joint action of France, Germany, Norway and Sweden, to amend Regulation No. 107 and Regulation No. 118 to enhance fire safety in vehicles of categories M2 and M3”, UNECE, Geneva, Switzerland,
21. “Concerning the Adoption of Uniform Technical Prescriptions for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these Prescription”, UNECE, Geneva, Switzerland, 2016.
Bus Fires in the United States
Update:
Passenger and Driver Evacuation Training

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ABSTRACT

Bus fires remain a serious safety issue in the USA. There appears to be little change in the number of fires even with the availability of fire suppression systems and greater awareness of the problem. This paper reviews Lancer Insurance Company's 5 last years of bus fire data with an emphasis on 2014-2016 years. The data includes statistical analysis of the number of bus fires, the age of vehicles as well as the overall cost impact of these claims. A careful review of the cause of each fire, location of ignition as well as prevention issues are discussed in relation to the economic impact on the industry. This will include the cost of vehicle replacement, injuries as well as the loss of customers. The second part of the paper will focus on the critical issue of driver training and passenger evacuation. An attempt will be made to compare the impact of bus fires on companies with active driver and evacuation training vs. those without training programs.

KEYWORDS: bus fires, evacuation, driver training

DESCRIPTION, HISTORY AND CLAIMS DATA

Lancer Insurance Company maintains data on bus fires reported as claims by our policyholders. This data is Lancer specific and only reflects the overall frequency and severity of bus fires reported to Lancer. Since 2007, we have had over 250 bus fires reported to our claims department. This represents 1% of our frequency (number of claims), but 6% of our overall severity (cost of claims)

- Since 2007- 250 Bus Fire Claims
- 220 – Charter and Tour Buses
- Percentage of Fires to Vehicles Insured is Increasing
- 1% of Frequency
- 6% of Severity

The severity is quite high in relation to the frequency and the average cost of a bus fire has risen from $80,000 (5 years ago) to over $120,000 in 2015. This increasing cost and lack of reduction in frequency is a serious issue and has caused Lancer to invest resources into determining cause, prevention as well as passenger and driver training. The goal of these efforts is to reduce the number of bus fires through prevention and further eliminate the potential for passenger injury and/or death. The majority of our bus fire claims are “engine” based (60%) and another 20% are wheel/brake related. Lancer has spent over $30 million settling bus fire claims, but that only represents vehicle physical damage and not passenger bodily injury because we have had few if any passenger injuries reported as a result of bus fire claims. This can easily change dramatically, however, if even one bus fire claim includes injured passengers.

- 250 Fires since 2007
- 30-40 Fires A Year
- Average Cost- $120,000 (Large Increase)
- Very Little Subrogation
- High loss adjustment expenses
- 170-Engine, Electrical, Parts Failure (60%)
- 60-Wheel Well, Tire, Brakes, Driver (20%)
- 10 Arson, Other Bus Fire
- 10 Unknown

Since 2007, Lancer Has Spent Over $30 Million Managing Bus Fire Claims

High Physical Damage, Low Bodily Injury; That Can Change With One Event

Comparing bus fire claims to other more common bus claims identifies several issues of concern including the fact that the severity of bus fire claims is only exceeded by the industry’s most common claims including, Rear End and Sideswipes which represent 21% of the overall cost of claims. It is interesting to note that there are two other types of claims with very low frequency; Ran off Road and Pedestrian Hits that have high claims cost and both of these involve passenger/pedestrian injury. It can be expected then that if there were passenger injuries during a bus fire, the cost of the claim would be exponentially higher.

Cost of Bus Fire Claims 1% of frequency and 6% of severity is only Exceeded by the Following Claims:

- Rear End/Sideswipe – 32% freq- 21% severity
- Ran Off Road 1% freq- 14% severity
- Pedestrian Hit 1% freq- 12% severity

CAUSE AND PREVENTION

When reviewing causes, it is important to note that the Lancer data may be limited for several reasons including the following: only buses covered for Physical Damage will result in a paid claim, some claims are unreported because of this or the fact that there may be a high deductible and the value of the bus may be lower than the deductible amount. Further, if there is limited damage to the property or area surrounding the bus, the bus is older and high mileage and there are no medical/physical injuries, the policyholder may not report the event. Therefore, the true frequency and severity of fire claims may be unknown or understated.

- Not All Buses Are Insured for Physical Damage
- Unreported Claims
- No Physical Injuries
- Limited Property Damage
- Low Value Of Bus (Age and Mileage)
- High Deductible Amounts

Based on our causation studies and claims data because the majority of bus fires are engine based, several maintenance, driver training and passenger training efforts may be useful.

- Inspect All Fuel Lines and Hoses
- Check All Wiring To Avoid Electrical Fires
- Clean Engines Regularly
- Follow All Manufacturer Maintenance Recommendations and Recalls
- Be Careful Of Underinflated Tires
- Don’t Drive On Flat/Overheated Tires
- Train Drivers On Pre-Trip Inspections
Expand Maintenance to Include Additional Engine, Electrical, Turbocharger, Fuel Line Inspections as Well as Repairs and Replacement

When it comes to passenger and driver issues, the first and most important step is to provide a safety announcement at the beginning of each trip and as often as necessary, making sure the passenger are well aware of how to exit the bus in the case of an emergency. Second, driver training on bus evacuation will assist the driver when faced with a bus fire. Doing this before any event and on a regular basis goes a long way towards a successful evacuation.

- Train Drivers About What To Do If There Is A Fire
- Evacuation Training, Use of Fire Extinguisher Training and Use of Fire Suppression and Tire Monitoring Systems
- Passenger/Customer Safety Announcements that Include Evacuation Procedures
- Improve Routine Maintenance and Engine Cleaning Programs

Establishing and evaluating the maintenance program on a regular basis may assist in managing this risk before the engine or wheel wells are involved. Additional tire monitoring, brake inspections and preventive maintenance is very important. Finally, monitoring all manufacturer recalls, using manufacturer recommended replacement parts and buying buses with fire suppression systems are all critical to solving this very expensive problem.

- Expand Tire, Wheel Well Inspections, Maintenance and Repair
- Only Use Manufacturer Recommended Replacement Parts and Follow or Use Manufacturer Installation or Installers for Any Interior Electrical Components
- Include Fire Suppression and Tire Pressure Monitoring Systems When Purchasing a Bus

PASSENGER TRAINING/ANNOUNCEMENTS

The safety announcement script you use is very important. See below for a sample of a script available from Lancer Insurance Company. This script is available in audio and video and adapted for the vehicle made by the major bus manufacturers. It is supplemented by the additional script of the fire extinguisher location on the vehicle (by manufacturer). The use of a passenger safety message is very important when attempting to defend the cause of a claim. Alerting passenger to the emergency exit windows, roof hatches and how to evacuate the bus is an important safety measure and good customer service in general.

- Your coach is equipped with three emergency exits, the main door in the front of the vehicle and two roof hatches. Additionally, there are several specially designed emergency exit windows on each side of the coach that are clearly marked with decals. Please take a moment now to look for and read the signs indicating the location and operation of these exits.
- If you must evacuate, rely on your trained driver and, if available, your group leader or tour director for instructions on moving to the safest place possible outside of the coach. If conditions permit, we encourage you to use your cell phones to call 911.

1. VanHool
   - Smoking or lighting matches or lighters on the motorcoach is strictly forbidden, even in the restroom. In the unlikely event of its need, a fire extinguisher is available on board and located on the right side floor along side the driver’s seat. Please advise your driver or tour director immediately if you see or smell smoke or anything unusual.

2. Setra
   - Smoking or lighting matches or lighters on the motorcoach is strictly forbidden, even in the restroom. In the unlikely event of its need, a fire extinguisher is available on board and
located under the step next to the driver’s seat area. Please advise your driver or tour director immediately if you see or smell smoke or anything unusual.

3. Prevost
   - Smoking or lighting matches or lighters on the motorcoach is strictly forbidden, even in the restroom. In the unlikely event of its need, a fire extinguisher is available on board and located under the front row seats on the door-side of the coach. Please advise your driver or tour director immediately if you see or smell smoke or anything unusual.

DRIVER TRAINING UPDATE

Lancer Insurance Company has been evaluating two aspects of bus fires and driver training. The first is: are companies conducting driver training and the second is: If they are, what is the best way to approach the subject matter.

Since January 2006, training has been provided to over 500 drivers representing 25 policyholder companies and several state association meeting attendees. Prior to the training, it was determined that only 2 companies had provided specific bus fire evacuation training as part of the driver training/retraining curriculum. Based on this limited data, Lancer is in the process of establishing and distributing a brief training module on bus fire evacuations. The training goal is to reach an additional 2,000-5,000 drivers during 2017. The training module will be provided via download and/or live streaming on the Lancer website, Safety and Loss Control section.

- To date- In Person Fire Evacuation Procedure Training has been provided to:
- 25 Lancer Policyholder companies and at 4 State Association meetings covering over 500 drivers
- The goal for 2017 is to increase that number of driver by 2,000 and include written/video training
- Of the 25 companies that accomplished training, only 2 had done training previously
- Of the 2 companies, only 1 had done “hands on” bus evacuation in conjunction with a local fire department
- Conclusion: Bus Fire Evacuation Training is a necessary element of driver training

There are several models available to our policyholders, including: both didactic, classroom training and specific exercises targeting actual bus evacuation experiences. It is suggested that when drivers are being trained, local fire departments be included in the training. They can assist in teaching about the impact and dynamics of fire as well as be instructed how to open a bus door, where to find the battery turn off as well as how the emergency window work on a bus. Including customer representative, tour guides and tour operators in this training is an excellent way to make sure everyone involved in the transportation will have knowledge, experience and direction should a bus fire occur.

- Didactic classroom training
- Hands on, actual bus evacuation event
- Joint training with local fire department including training Fire Department personnel how to open the door, turn off power and manage heavy emergency windows
- Joint training with both Tour Guides and Customer groups

DRIVER TRAINING

The following 8 step guide provides a starting point for drivers to learn and practice bus evacuations. The time to practice evacuating a bus is long before a fire happens. The same holds true for a fire suppression system or fire extinguisher. The time to learn to use them is before the event when you have time to think about and integrate the learning process. This suggested 8 step program is just that,
a suggestion and one that may make a difference in the event of a true emergency. There are other models and approaches that can be utilized and this one does not cover every possible situation. Consider using these guidelines as you train your drivers and provide your customers with as much safety related information as possible before and during the trip.

- 1- Pull the bus over to the safest spot available. A quick decision is necessary but using good judgment about when and where to stop the bus is important. Turn off the ventilation system and then the engine.
- 2- Make an announcement over the intercom system and/or by standing up and in a loud voice telling the group there is a problem and they need to "EXIT THE BUS AS QUICKLY AS POSSIBLE....LEAVE ALL LUGGAGE....ASSIST ANYONE AROUND YOU - then call 911. Second announcement should be "THERE ARE EMERGENCY EXIT WINDOWS ON EITHER SIDE OF THE BUS...LIFT THE LATCHES, PUSH THE WINDOW OUT AND EXIT THE BUS...LEAVE ALL LUGGAGE." Consider non-English speaking passengers and attempt to make the evacuation message known to them as well.
- 3- Drivers should assist with the evacuation by not being in the doorway but either assist passengers (from the driver's area) or at the base of the steps assisting and DIRECTING PASSENGERS TO THE SAFEST SPOT TO GATHER (away from the bus).
- 4- If there is a host/tour guide on the bus, the host should direct passengers to the safest spot and call 911, etc. and assist passengers as necessary. If passengers are attempting to exit via the emergency windows, anyone outside of the bus who is able should be asked to help those using the emergency window exits. The driver and host should be trained about how the height of the bus and weight of the windows may be difficult to manage and practice using the windows. If there is no host, the driver should ask for passenger(s) assistance with the evacuation. Consider identifying a passenger(s) before the trip who will be designated as a volunteer to assist the driver; similar to the "exit row" responsibility on a plane.
- 5- The driver and or host should assist every passenger out of the bus to the best of their ability and not exit the bus until the evacuation is complete (within reason of the circumstances).
- 6- The driver and host should continue to make the announcement as noted in #2 throughout the evacuation because people in the back, people sleeping, hard of hearing or disabled may not recognize the danger.
- 7- If there are disabled passengers, generally there is not time to use the lift so "lift and carry" may be an option if you engage other passengers. Drivers should have some training on the best methods of "lift and carry" if there is a lift door on the bus and it is operable, the driver should open it as soon as possible because it provides another means of escape.
- 8- Move passengers away from the bus to the safest available location, call dispatch/company/911 again if necessary

CONCLUSION

The epidemic of bus fires will continue. However, with the addition of advance fire management technology, good maintenance programs coupled with customer and driver training, it is very possible to keep the impact of bus fires low and save human lives.

- Bus Fires Will Continue
- Install Fire Suppression and Tire Pressure Monitoring Systems
- Increase and Improve Maintenance
- Train Drivers On Prevention and Evacuation
- Provide Passengers With Safety Information
- Train Passengers on Evacuation
Analysis of Fire Protection of UK Buses from 1964 to 2013

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ABSTRACT

Buses are the most risky form of transport in terms of fire protection. Recent data in the UK show that the probability of bus fires is 2.3 times higher than cars, 8 times higher than trains, and 2.7 times higher than ships. This is in great part due to the lower fire safety requirements in buses, which are less stringent than other modes of transport. Fire protection engineering is made of different layers (i.e. prevention, passive systems, detection, evacuation, and suppression). While all these layers have a role, they are not equally important, either in terms of benefits or costs. This paper presents a systemic approach to quantify the impact of the prevention layer to UK buses using statistics from 1964 to 2013. The statistics in the UK collected for this paper show that the number of bus fires has increased exponentially from 1964. This increase is related to a larger number of licenced buses per year. During this period, European regulations have been established in order to reduce the probability of fire in buses. The cross-analysis of changes to fire protection standards and statistics on bus fires shows that prevention has reduced the probability of a fire in the UK by 1.589±0.013.

KEYWORDS: buses, prevention, layers of fire protection, systemic.

INTRODUCTION

We recently learnt the sad news of 43 fatalities caused when a bus caught fire immediately after a collision in Puisseguin (France) on 23rd October 2015 and the 17 fatalities in a suspected arson attack on a public bus in Ningxia (China) on 5th January 2016. Buses, which can carry 30 passengers or more, have the potential for a greater number of deaths and injuries and significant property losses from fire. In fact, buses are amongst the riskiest forms of transport regarding the fire protection.

According to the statistical data in the UK [1][2] the probability of fire in a bus is 2.3 times higher than in a car, and similar to heavy goods vehicles (HGV) [1]. Moreover, the probability of bus fires in the UK is 8 times higher than trains, and 2.7 times higher than ships [3] (In this paper, the probability of fire in a mode of transport is obtained as the annual number of vehicle fires per 1000 licenced vehicles). This is in great part due to the lower fire safety requirements in buses, which are less stringent than for the other modes of transport.

For example, fire prevention requirements in buses [4][5] do not cover aspects such as the limitation of peak heat release rate, the smoke yield or the toxicity unlike trains, planes and ships [6].

In Europe, the fire protection in buses was first standardized in 1995 by the European Directive 95/28/EC regulating the burning behaviour of materials used in the interior construction of certain categories of motor vehicles [4]. This first directive was followed by two main European regulations, Regulation No. 118 [5], which is the adapted from the Directive 95/28/EC, and Regulation No. 107. On the top of flammability tests, UNECE Regulation No.107 [6] improved the fire protection of buses in Europe in 2001 (i.e. no flammable soundproofing material can be located in the engine compartment, a partition shall be fitted between the engine compartment and any other source of heat, the use of alarms in the engine, fire extinguishers and first-aid equipment).
Fire protection engineering shows that safety is made of a series of layers [7] (prevention, passive systems, detection, evacuation, and suppression). While all these layers have a role [8], they are not equally important, either in terms of benefits or costs.

This paper presents a systemic approach to analyse the impact of the prevention layer to the specific system of buses (multiple passenger road vehicles) in the UK. We quantify the impact in terms of the reduction of bus fires.

The proposed methodology is based on the cross-analysis of the standards of fire protection in buses that define the presence of the layers, and the statistics of bus fires in the UK. This analysis reveals how the improvement of the prevention layer has reduced the number of bus fire over years.

**FIRE ESCENARIOS IN BUSES**

Fire statistics in the UK, Sweden and USA highlight three fire scenarios of importance for buses [9-11] based on the conditions that describes the ignition location of fire: fire within the passenger compartment, fire within the engine compartment and fire within the wheel well compartment (see Figure 1).

![Figure 1](Location_of_bus_fire_scenarios.png)

**Fire within the passenger compartment.**

The passenger compartment is where the occupants are situated (passengers, drivers and crew) [11]. Modern buses use materials such as cotton, wool or cellulose that can burn to provide an appropriate comfort level (e.g. comfortable seats, air conditioner, curtains and blinds) for passengers. The main ignition sources [9, 10] within the passenger compartment are electrical failure or malfunction, intentional actions (arson) and accidental ignition by any passenger (cigarette, lighter).

**Fire within the engine compartment.**

This compartment is the separate space into which the engine is installed. There are multiple flammable materials such as fuel, oil, plastic and rubber. Liquids are especially flammable such as engine oil (diesel or gasoline), transmission oil, antifreeze and washer fluid. The main sources of ignition [17] are fuel leaks combined with an electrical failure.

**Fire within the wheel well.**

This compartment is where the wheels, transmission system and brakes are installed. This contains several flammable materials in the form of solid substances such as rubber of the tyre and plastic and liquid substances (brake fluid and oil/lubrication for bearing) [12]. Overheated brakes, frozen wheel bearings, underinflated tires or lack of lubrication, which cause friction, can be a source of ignition for a bus fire in this area.

**LAYERS OF FIRE PROTECTION IN UK BUSES**

As described in section 1, fire protection engineering shows that safety is made of a series of layers (prevention, passive systems, detection, evacuation, and suppression). How these layers are defined depends on the application scenario. The following descriptions are based on buses with an emphasis on the prevention layer. In addition, this section identifies the links between the European regulations and these layers of fire protection.
Prevention layer

The aim of the prevention layer is to avoid a bus fire the in first place or to reduce its size. This is based upon the disruption of the fire triangle – oxygen, heat, and fuel–. As eliminating oxygen is not a viable option, prevention is focused on fuel and ignition (heat). The prevention layer is divided into three sublayers: flame retardancy, fuel control and avoidance of source of ignition.

**Prevention by flame retardancy.** For the passenger compartment, this is based on passing the required flammability tests of the interior materials [13, 14]. The engine compartment is especially prone to fire due to the fuels, oils, and high temperatures within it. Since 2012, regulation 118 requires flammability test of materials in the engine compartment. In the wheel well compartment, the flammability tests are not required to date.

**Prevention by fuel control.** For the passenger compartment, fuel control is based on eliminating or reducing the amount of fuel within it. Fuel is presented in the engine and wheel well compartments (e.g. diesel or gasoline, engine oil, transmission oil, brake fluid, oil/lubrication for bearings). However, it is necessary to avoid fuel leakage within these scenarios in order to prevent a fire. In this sense, the fuel control is currently based on an appropriate level of maintenance by strictly adhering to maintenance schedules [15].

**Prevention by eliminating the source of ignition.** There are two main sources of fire in passenger compartments: electrical failure and intentional or accidental actions. To eliminate electrical failures this layer requires an appropriate maintenance level by strictly adhering to maintenance schedules [10]. For the passenger compartment, the driver and passengers will be responsible for monitoring any suspicious action performed by other passengers that can cause a fire, intentionally or unintentionally. In the engine compartment, the prevention by eliminating the source of ignition is centred on avoiding electrical faults and hot surfaces. Wheel well compartment is focused on avoiding or mitigating electrical faults and friction. The most appropriate measure for passenger and wheel well compartments is an appropriate level of maintenance achieved by strictly adhering to maintenance schedules [10].

Passive Systems layer

The aim of passive systems is to avoid fire spread between compartments. The passive systems layer is focused on compartmentalization as it is required by the UNECE Regulation No. 107. In actual buses, the engine compartment is separate from the passenger and wheel well compartments using materials which are fire resistant and using flame retardants. Studies such as the one done by NIST [13], shows how a fire in the wheel well compartment spreads to the passenger compartment. However, compartmentalization is not required in the wheel well.

Detection layer

The aim of the detection layer is to detect and warn about flames or smoke as soon as possible. Quick fire detection reduces the reaction time to face a bus fire, which is a key factor on favouring the role of the other fire safety layers. In passenger compartments, the detection layer is focused on two aspects: visual detection and automatic detection. The driver and passenger monitoring will allow smoke and fire to be visually detected. From 2014, alarm systems detecting smoke or excess temperature shall be installed in the toilet compartment, driver’s compartments and other separate compartments such as the baggage area. These systems should provide the driver with an acoustic and visual signal in the driver’s compartment. The engine compartment is required to be equipped with an alarm system [6] including acoustic and visual signals in the driver’s compartment. No regulations have been established yet regarding detection in the wheel well.
Evacuation layer

The aim of the evacuation layer is to permit the passengers to escape quickly from a bus fire before the conditions become untenable. The evacuation layer is only part of the passenger compartment which needs an appropriate number of exits with at least two exit doors [16]. This is normally stated based upon the maximum number of passengers within the bus. An important factor is an appropriate evacuation procedure and training. Drivers and cabin crew need to be trained for an appropriate and fast reaction in case of fire. Occupant actions and decisions during evacuation is a critical factor [17]. The evacuation layer can include safety announcements during trips in order to inform passengers about evacuation procedures in case of a bus fire.

Suppression layer

The suppression layer is focused on extinguishing the fire at the earliest stages in order to avoid growth and spread [18]. To date, no regulation has established the mandatory use of suppression systems in buses. Nevertheless, studies such as [19] in Sweden and the US show the advantages of using these systems. In this sense, the Swedish insurance companies require buses to be equipped with suppression systems in the engine compartment since 2004. SP has gathered fire statistics in Swedish buses in two datasets, from 1996 to 2004 [9 and from 2005 to 2013[20]. These two datasets do not allow SP to quantify the effectiveness of the suppression system. However, table 1 of section 2.1 shows a downtrend in percentage of fires initiated in the engine compartment.

In passenger compartments the suppression layer is based on manual and automatic suppression. Regulations [6] establish that buses must be equipped with fire extinguishers, and that at least one should be located near the driver. The driver and cabin crew must be properly trained for using the fire extinguishers. The passenger compartment should be equipped with suppression systems, especially in non-visual access areas such as the toilet and baggage compartment.

STATISTICAL DATA ON FIRE INCIDENTS IN UK BUSES

A key aspect to quantify the impact of the layer of fire protection is the statistical data on bus fires. The quantification of the benefits and costs depends on the availability of the data regarding the number of bus fires, deaths and injuries.

The information about fire events in buses is limited. Only a few datasets on bus fires have been observed in Sweden [9, 20], Norway [9] and the USA [14], with some years in Germany and Finland [21-23].

This paper includes a novel database of bus fire statistics in the UK from 1964 to 2014 with a gap in the data between 1970 and 1983. The available data is focused on the number of bus fires per year as the information about the number of deaths and injuries is limited. The number of deaths and injuries is only registered between 1964 and 1969 [19], and between 2010 and 2014. The range of years is too narrow to quantify how much each layer impacts on the number of casualties. This data has been obtained from the electronic bulletins published by The Department of Communities and Local Government in the UK [1]. Those bulletins detailed statistics on fires, casualties and false alarms.

In spite of the limited worldwide data on bus fires, the UK bulletins included the number of bus fires since 1996, collecting statistics since 1984. An additional dataset on bus fires in the UK has been observed for the period between 1964 and 1969 [24]. This Fire research note was published in 1972 by the Fire Research Station at BRE. This dataset includes annual data on the number of bus fires in this period as well as additional information such as the number of deaths and injuries, location of the fire in the vehicle and the year of manufacture of vehicle in which fire occurred.

In total, a dataset on bus fires between 1964 and 2013 with a gap between 1970 and 1983 has been used in this paper. It should be noted that these statistics cover the number of bus fires per year. Both,
the UK bulletins and the fire research note include the number of fire events registered in buses, coaches and minibuses, with no distinction between these three categories.

- Buses: Over 22 passengers (including passengers standing)
- Coaches: 17 or more seats (with no passengers standing)
- Minibuses: From 8 to 22 passengers (including passengers standing)

On the basis of this paper, the probability of bus fires is defined as the number of fire events per 1000 licenced buses. In order to obtain the annual probability, the size of bus fleet per year in the UK is required. This information was collected from the Department of Transport. Figure 2 shows the data on the annual number of fire events and the annual probability (number of bus fire per 1000 buses licenced) of bus fires in the UK.

![Figure 2: Number of bus fires and probability of bus fires from 1964 to 2013](image)

As shown in Figure 2, an average of 327 bus fires per year was registered in the UK between 1964 and 1969. This average more than doubled to 761 for this period between 1984 and 2013. The large increase in the number of bus fires is in part due to the increase in the size of bus fleet during this period. A total of 8,600 buses were licenced in 1964, and the fleet had nearly doubled by 2013 to a size of 16,441 buses. Since 1994, the bus fleet increased annually with an average of 11,200 new buses per year.

**QUANTIFICATION OF LAYERS OF FIRE PROTECTION**

Our key method for quantifying the layers of fire protection is a cross analysis of the regulations and the annual statistics in bus fires. The changes in the regulations over the years led to the strengthening of layers of fire protection in buses. The bus fleet manufactured after a regulation change contains the corresponding enhancement. The replacement of the bus fleet in the UK is gradual and during some years after a layer is included or boosted, the total bus fleet licenced in the UK contains both, old (pre-regulation buses) and new buses (post-regulation buses). The size of the post-regulation bus fleet will increase annually, as the pre-regulation bus fleet will decrease.

**The evolution of the bus fleet in the UK**

The Department for Transport in the UK registers annually, the total number of buses in the UK as well as the number of new buses licenced each year. Based on this information, it is possible to evaluate the evolution of the fleet after a standard modification.

As section 2 of Figure 3 shows, the European Directive 95/28/EC and UNECE regulation No. 107 enhanced the prevention layer twice, in 1995 and 2001 respectively. The bus fleet manufactured from 1995 to 2001 contains the prevention layer improved by the European Directive 95/28/EC. The bus fleet manufactured since 2001 also includes the improvements provided by the UNECE regulation.
No. 107. The following nomenclature will be used throughout the rest of the paper.

- $y_{1995}$ – Pre-1995 bus fleet or the bus fleet manufactured before the European Directive 95/28/EC in 1995;

On the basis of the statistical data from the Department of Transport in the UK (total number of buses and new buses licenced per year), the evolution of the size of these three bus fleets ($y_{1995}$, $y'_{1995}$ and $y''_{2001}$) can be obtained (see Figure 3).

![Figure 3](image)

*Figure 3  Annual proportion of each bus fleet between 1995 and 2013*

As shown in Fig.3 and under the reasonable assumption that the bus fleet is progressively replaced, from 1995 to 2000, $y_{1995}$ decreases as $y'_{1995}$ increases. In addition, there is a period between 2001 and 2010, when the three bus fleets exit (in different proportions) at the same time. After 2010, only $y'_{1995}$ and $y''_{2001}$ exist.

**The quantification of prevention layer in UK buses.**

As has been explained in section 3, key aspects to identify and quantify the layers of fire protection are statistical data and its level of detail and fire protection regulations.

During the period of analysis (1964 and 2013) only the changes in the regulations in 1995 (prevention layer) and 2001 (prevention, passive system and evacuation layers) affected the number of bus fires. Passive system and evacuation layers do not affect the number of bus fires, so the available data (annual number of bus fires and buses licenced) allows the authors to identify and quantify how much the prevention layer has reduced the number of fires during the years in UK buses.

On the basis of a wider statistical dataset and fire regulations, the proposed method can be extrapolated to other scenarios and layers.

We can quantify the impact of the prevention layer (or any other layer) by comparing the probability of fire before and after changing the fire protection regulation which affects that layer.

In buses, the impact of the prevention layer is obtained by assessing the probability of fires in the buses manufactured before a regulation change versus the probability of fire in buses manufactured
after a regulation change. The comparison of these probabilities will show how much a change in a regulation has impacted to the number of bus fires.

This paper is based on the hypothesis that all the buses of each fleet ($y_{1995}$, $y'_{1995}$ and $y''_{2001}$) have the same level of fire protection. For this reason, the probability of fire in each bus fleet is similar, and it is assumed that during the years of interest, that probability is constant.

As section 3 explains, the probability of bus fire in this paper is defined as the number of bus fires per 1000 licenced buses. In addition, the following nomenclatures will be used throughout the paper:


Based on the information of how the bus fleet replacement takes place in the UK after the regulation modification in 1995 and in 2001 and the previous hypothesis, Eq. (1) calculates the probability of fire in pre-regulation ($p$) and post-regulation buses ($p'$).

$$f_i = py_i + p'y'_i$$

Where, $f_i$ is the number of bus fires in year $i$, $y'_i$ is the number of buses in year $i$ manufactured before the regulation change and $y''_i$ is the number of buses in year $i$ manufactured after the regulation change.

Considering the three bus fleets during the years of interest and based on equation 1, the following equation 2 is proposed as a functional relationship to obtain the probability of fire in each bus fleet ($p_{1995}$, $p'_{1995}$ and $p''_{2001}$).

$$f_i = p_{1995}y_i + p'_{1995}y'_i + p''_{2001}y''_i$$

Based on the annual number of bus fires ($f_i$) and the three bus fleets ($y_{1995}$, $y'_{1995}$ and $y''_{2001}$), the probabilities of bus fires ($p_{1995}$, $p'_{1995}$ and $p''_{2001}$) are calculated by optimizing equation 2. The mathematical optimization seeks to minimize the difference between the numbers of bus fires each year between 1995 and 2001 registered in the annual bulletins of fire statistics and the optimized frequency of bus fire $f_i$.

The best-optimized probabilities for the frequency of bus fires are:

$$p_{1995} = (4.75\pm0.04)$$
$$p'_{1995} = (4.21\pm0.04)$$
$$p''_{2001} = (2.99\pm0.04)$$

The error obtained is the average relative error in the optimization of these three variables. The impact of each regulation modification is evaluated by dividing the probabilities of bus fires before and after a change.

Based on the optimized values for $p_{1995}$, $p'_{1995}$ and $p''_{2001}$ and equation 2, Figure 4 shows the best-fit bus fires.
In order to smooth out short term fluctuations in the number of bus fires, the moving average was obtained. As Fig.4 shows, Eq.2 (using the best-optimized probabilities) predicts the number of bus fires in the UK with a high accuracy.

The variability between the number of bus fires (and its moving average) and the best-fit bus fires in Fig.3 is mainly caused by the assumption of the constant probabilities. It should be noted that the updates in the regulations may slightly affect these probabilities during a period. Based on the best fit probabilities, we can compare the probability of bus fire immediately after and before the regulation changes so that we can quantify the impact of the prevention layer.

The comparison of the probabilities $p_{1995}$ and $p_{1995}'$ allows us to quantifies how much the enhancement of the prevention layer in 1995 reduces the frequency of bus fires.

$$Q_{1995} = \frac{p_{1995}}{p_{1995}'}$$  \hspace{1cm} (3)

This is:

$Q_{1995} = (1.128\pm0.007)$

As expected, the enhancement of the prevention layer led to a decrease in the number of bus fires. Equation 3 shows that the 95/28/EC in 1995, which is based on flammability tests for the passenger compartment, reduced by 1.128 times the number of bus fires.

To quantify the overall impact of prevention layer ($Q_p$) reducing the frequency of fires in UK buses, equation 3 is extrapolated to $p_{1995}$ and $p_{2001}''$ so that:

$Q_p = (1.589\pm0.013)$

Note that the errors of $Q_{1995}$ and $Q_p$ are estimated as an indirect measurement of equation 3 considering the relative errors of the probabilities.

The analysis of layer of fire protection in buses shows that the prevention is a key aspect as the regulations has been focused on improving this layer. The enhancement of the prevention layer over the years has reduced by 1.589 times the overall number of bus fires. Even when the probability of bus fires is higher than other modes of transport, fire safety remains substantially lower and the applicability of some regulations such as the flammability tests is still under discussion.
CONCLUSIONS

In this paper, we present a novel methodology to quantify the impact of each layer of fire protection engineering, in terms of benefits and costs. This methodology is applied to buses in the UK.

A novel dataset of fire events in UK buses from 1964 and 2013 has been used in this paper. This dataset is extracted from the annual bulletins on fire statistics published by the Department for Communities and Local Government and it is focused on the annual number of bus fires.

Two changes in the standards have affected to the layers of fire protection in this kind of scenario. The 95/28/EC in 1995 (updated by the UNECE Regulation N.118), with the flammability requirements in the passenger compartments and the UN ECE Regulation N.107 in 2001 and its updates, enhancing the prevention, the passive system, evacuation and detection layer.

Based on the available information, this paper is focused on the prevention layer and how much the enhancement of this layer reduces the number of bus fires in the analysed period.

The key method for quantifying the impact of the prevention layer is a cross-analysis of the regulation of the fire protection in buses and the annual statistics in bus fires. We analysed the probability (defined and the number of bus fires per 1000 licenced buses) of fire before and after the regulation changes in order to quantify how much the prevention layer reduces the frequency of fires.

The buses manufactured after the modified standard contains the corresponding enhancement. During the analysed period, three bus fleets are identified: buses manufactured before 1995, buses manufactured between 1995 and 2001 and buses manufactured after 2001. The data provided by the Department for Transport on the number of buses licenced in the UK allows calculating the progress of each bus fleet during the period.

The optimization of equation 2 allows obtaining the probably of fire for each bus fleet. As Fig.3 shows, the best–fit bus fire predicts the number of bus fires with a high accuracy.

The analysis of these probabilities reveals that buses manufactured before 1995 were 1.128±0.007 times more likely to catch fire than after 1995. Comparing the probability of bus fires before 1995 and after the modification in 2001, we can conclude that the prevention layer has reduced the overall number of bus fires 1.589±0.013 times.

The results show the importance of the prevention layer in buses and how much each modification has impacted in the number of bus fires. However, fire safety remains substantially lower in buses than in cars and other means of transport and under discussion.

To identify the strengths and weaknesses in the layers of fire protection in buses is a key aspect for further development of current regulations.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of Bromine Science and Environmental Forum (BSEF). We are grateful to the member of the Advisory Board for their support to N-LAYERS Project, Kathleen Almand (National Fire Protection Association, USA), Yi Wang (FM Global, USA), Chris Salter (BRE, UK), Steffen Duelsen (Bombardier, Australia), Mike Hagen (Fire Safety Platform, UK), and Jonas Brant (SP Technical Research Institute of Sweden, Sweden).

REFERENCES

5. UNECE Regulation No. 118: Uniform technical prescription concerning the burning behaviour and/or, the capability to repel fuel or lubricant or materials used in the construction of certain categories of motor vehicles, UNECE, Switzerland, 2012.
6. UNECE Regulation No. 107: Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction, UNECE, Switzerland, 2014.
Experimental Analysis of Human Evacuation
From Bus Fire

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\textsuperscript{2}Kanazawa University, Graduate School of Natural Science & Technology, Japan
\textsuperscript{3}Kanazawa University, Faculty of Mechanical Engineering, Institute of Science and Engineering, Japan
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\textsuperscript{5}Central Police University, Department of Fire Science, Taiwan (R.O.C.)

ABSTRACT
Passenger bus fires are relatively rare but do occur. On May 7, 2012, a bus fire incident occurred in the Hsuehshan Tunnel in Taiwan, which resulted in the death of 2 people and 34 people sustained injuries due to traffic accident and smoke inhalation. This led to increased public concern about the issue of bus fires in tunnels.[1]

In order to study the situation of evacuating a bus, a series of experiments were conducted in Japan to measure the evacuation flow rate of passengers leaving the bus in different conditions.

Based on the results, the evacuation flow rate of a bus with a single exit was between 0.57 and 0.94 person/second.

The evacuation flow rate decreased when passengers escaped from a bus using the emergency exit, which indicates that a high emergency exit is not favorable for evacuation.

Moreover, the participants were mostly aged between 20 and 30 years; therefore, it was not easy to demonstrate the influence of disabled people on evacuation flow rates in all cases. However, a delay in evacuation time was observed when participants wore an “elder set,” which caused their actions to slow down.

KEYWORDS: Bus Fire Evacuation, Evacuation Flow Rate, Exit Type, Elder Set

INTRODUCTION
Vehicle fires in road tunnels can cause serious casualties, particularly in buses that carry many passengers. Occurrence of any fire easily arouses public concerns.

Numerous theories providing adequate analysis about evacuations in fire events and information about how the event can be divided into different stages, as well as the numerous influencing factors have been reported. However, there is insufficient analysis on the specific influence of crowd dynamics or bus geometries (such as the number of exits and seats).

Since a bus carries a larger number of people, more injuries and deaths can be expected in case of a fire than in passenger cars; this inevitably attracts more attention.

The bus fire in the Hsuehshan Tunnel that occurred at 1:27 p.m. on May 07, 2012, was a painful lesson.
The fire was caused due to a collision between a passenger bus and a small truck. From the review report of this bus fire incident, the following points can be noted:

- Emergency exits were narrow and therefore passengers had to escape from the bus one by one.
- Passengers attempted to pick up their baggage during evacuation
- Because of the vehicle collision, only one exit was available, which further hindered the rapid evacuation process.

Based on the points mentioned above, it can be noted that the issue of bus evacuations is important. In order to study human behavior during a bus fire incident and discuss some specific factors that affect evacuation, such as mobility of passengers, bus geometry, and baggage, a series of bus evacuation experiments were conducted in Japan.

**BUS EVACUATION EXPERIMENT**

**Experiment Procedure**
The bus evacuation experiments were conducted at the Kanazawa University in Japan. Several participants were arranged at different bus seats. When the experiment started, participants had to leave the bus to simulate the process of evacuating a bus in different conditions. The experiment was filmed to analyze the evacuation flow rate and evacuation behaviors.

**Bus Layout**
A medium-sized bus was used in the experiments, which had 28 seats and 2 exits, including an emergency door (see Figures 1, 2, and 3).

![Figure 1 Bus Type.](image1)

![Figure 2 Bus Inside Configuration.](image2)
Experiment Conditions
In order to analyze the evacuation behavior of passengers getting out of the bus and the specific influencing factors, several experimental conditions were proposed and shown in Table 1.

Table 1  Experiment conditions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Experiment Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior environment</td>
<td>Curtains is closed and lamp is turned</td>
</tr>
<tr>
<td>Smoke</td>
<td>Don’t use</td>
</tr>
<tr>
<td>Participants</td>
<td>16(Male : 15 : Female : 1)</td>
</tr>
<tr>
<td>Analysis item</td>
<td>1. Situation.</td>
</tr>
<tr>
<td></td>
<td>2. Disabled</td>
</tr>
<tr>
<td></td>
<td>3. Evacuating with/without baggage.</td>
</tr>
<tr>
<td></td>
<td>4. Exit type.</td>
</tr>
<tr>
<td>Others</td>
<td>Don’t take injury situation into account.</td>
</tr>
</tbody>
</table>

The following influencing factors were included for analysis:

(1) Situation
Conducting evacuation experiments in a real fire situation is dangerous. However bus fire evacuation analysis is significantly important. In order to make the experiments simulate a fire evacuation, different situations were defined and the participants were instructed accordingly before every experiment.
A. Get off the bus: Participants in this situation were to imitate getting off the bus in a normal situation.
B. Normal evacuation: Participants in this situation were to imitate getting off the bus for an unknown safety situation. It was assumed that the participants were unaware of a fire accident outside of the bus.

(2) Disabled
This experimental condition was designed to account for disabled people and was divided into two cases. However, letting elderly passengers participate in this experiment is dangerous; therefore, an elder set was worn by participants to simulate an elderly person’s behavior (see Figure 4):
A. No elderly passengers in the bus
B. Two elderly passengers in the bus
(3) Evacuating with/without baggage

According to the CCTV record of the Hsuehshan Tunnel bus fire, passengers attempted to carry their baggage while evacuating the bus. The real impact of this behavior on the delays caused during an evacuation is still uncertain. Therefore, in this study, two phenomena were taken into account:

A. Carry baggage during evacuation (baggage shown in Figure 5)
B. Do not carry baggage during evacuation

(4) Exit type

The principle of escaping from a bus fire is that passengers should be expected to exit and move away from the vehicle, usually by their own means. An inadequate means for escape will be a threat to the safety of passengers. Considering the position of exits, it was deemed reasonable to expect that a fire or other emergency may render an exit unavailable. Exits must be true ‘alternatives’ and not capable of being rendered unusable. They should also be accessible without undue difficulty, easy to operate and negotiate and well marked. [2]

However, there are no consensus views on which exit design is suitable or accessible. Therefore, in this study, convenience and accessibility of different exit types have been discussed. In this experiment, the bus had two exit: one was a normal exit which was 0.36 m from the ground and had steps to allow passengers to walk easily, and another was an emergency exit, which was 1.4 m from the ground and involved moving a seat to be used (exit types are shown in Figure 6 and Figure 7).
Based on the abovementioned points, the conditions were defined as follows:
A. Using a normal exit to evacuate.
B. Using an emergency exit to evacuate.

Experiment Scenarios
According to the influencing factors mentioned above, experiment scenario combinations are shown in Table 2.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Situation</th>
<th>Baggage</th>
<th>Elder</th>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Get off bus</td>
<td>Yes</td>
<td>0</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 2</td>
<td>Normal Evacuation</td>
<td>No</td>
<td>0</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 3</td>
<td>Normal Evacuation</td>
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<td>0</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 4</td>
<td>Normal Evacuation</td>
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<td>0</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 5</td>
<td>Normal Evacuation</td>
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<td>2</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 6</td>
<td>Normal Evacuation</td>
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<td>2</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 7</td>
<td>Normal Evacuation</td>
<td>No</td>
<td>2</td>
<td>Normal exit</td>
</tr>
<tr>
<td>Case 8</td>
<td>Normal Evacuation</td>
<td>No</td>
<td>0</td>
<td>Emergency exit</td>
</tr>
<tr>
<td>Case 9</td>
<td>Reclining</td>
<td>No</td>
<td>0</td>
<td>Normal exit</td>
</tr>
</tbody>
</table>

Recording the Experiment
In order to record human behavior, two cameras were used. The detailed information is shown in Table 3 and Figures 8 to 10.
Table 3  Amounts and Position of Recording Tool.

<table>
<thead>
<tr>
<th>Recording tool</th>
<th>Surveillance cameras×4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Video cameras×2</td>
</tr>
</tbody>
</table>

| Observation position | Bus Inside, Entrance, Emergency exit |

Figure 8  Camera Configuration.

Figure 9  Camera in the Bus.

Figure 10  Camera out of the Bus.
Limitations of Experiment
Avoiding injury to the participants was the most important principle of this evacuation experiment. Thus, any hazard caused by a fire was not taken into account in these experiments, such as flames, high temperatures, smoke, and toxic gases.
In addition, injured passengers were also not taken into account because these situations were considered too complicated for the main research objective.

Definition of evacuation flow rate
In order to quantify the bus evacuation situation, in this study, evacuation flow rate is defined as to describe how fast passengers evacuate the bus. The formula is as follows (see Equation 1):

\[ Q = \frac{N - 1}{T} \]

Q: Evacuation flow rate (person/second)
N: Number of evacuees (person)
T: Time taken from the first to last evacuee to escape from the bus (second)

Evacuation Flow Rate Calculation
Some factors influence the passenger during an evacuation and cause a time delay, as well as congestion in the bus, which results in an unstable time interval. However, the objective of this research is to know the flow rate in a continuous evacuation process. Thus, in order to achieve a stable value, the evacuation flow rate of each case was calculated using the following process:

First, values which were greater than twice the average were excluded, and then the average value was recalculated. This procedure was repeated to produce a stable value that could represent passengers escaping from the bus in a continuous situation. The calculation process is shown in Figure 12.
Figure 12  Evacuation Flow Rate Calculation Process

The accuracy of the evacuation flow rate is also important. In order to calculate evacuation flow rate in more detail, video recording analysis was conducted. Accordingly, the video frame rate was slowed down to 1/30\textsuperscript{th} of a second to confirm the time when the passenger’s leg touched the ground (see Figure 13).

![Figure 12](image)

<table>
<thead>
<tr>
<th>Order of Evacuee</th>
<th>Time Interval</th>
<th>Order of Evacuee</th>
<th>Time Interval</th>
<th>Order of Evacuee</th>
<th>Time Interval</th>
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</thead>
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<tr>
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<td>2th-3th</td>
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<tr>
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<td>3th-4th</td>
<td>1.3333333333</td>
<td>3th-4th</td>
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<tr>
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<td>4th-5th</td>
<td>3.4</td>
<td>4th-5th</td>
<td>3.4</td>
</tr>
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<td>1.1666666667</td>
</tr>
<tr>
<td>10th-11th</td>
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<td>10th-11th</td>
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<td>10th-11th</td>
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<td>11th-12th</td>
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</tr>
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<tr>
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<td>1.235897436</td>
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<tr>
<td>Average Value +2</td>
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<td>Average Value +2</td>
<td>2.78952381</td>
<td>Average Value +2</td>
<td>2.471794872</td>
</tr>
</tbody>
</table>

Figure 13  Evacuation Time Point Determination.

RESULT AND CONCLUSIONS

Based on the results, the evacuation flow rate was between 0.57 and 0.94 person/second (see Figure 14). Comparisons with each case revealed that the evacuation flow rate was the slowest when passengers escaped from the bus using the emergency exit (case-8). The possible reason for this is linked to the height of the emergency exit, wherein the evacuee is required, with difficulty, to overcome the height of the exit point and try jump to the ground.

Second, most of the participants were male aged between 20 and 30 years and the data for females and participants wearing the elder set were limited and mostly comprised long time intervals. Thus, the data from female and participants wearing the elder set were usually excluded when the average evacuation flow rate was calculated. Therefore, the evacuation flow rate of case-8 did not significantly differ from the other cases.

Third, on comparing the time intervals for case-5, case-6, and case-7, it was found that the
participants wearing the elder set took much longer time compared to the other participants (see Figures 15 to 17). Due to the exclusion of these long time intervals when the average evacuation flow rate was calculated, the results would not reflect the influence of the elderly. However, if focus on the time interval between each participant, the impact of disabled indeed is exist.

Finally, the comparison between case-3 and case-4 did not clearly reveal the effect of baggage. It is assumed that baggage easily affects the passenger evacuation time; however, the baggage used in this experiment was possibly very small, so the results showed no significant difference.
CONCLUSION
Analyzing evacuation behavior from a bus was the main objective of this research. The results from this experiment can be concluded as follows:

- The evacuation flow rate using a normal exit was between 0.66 and 0.94 person/second, whereas the evacuation flow rate was 0.57 person/second when using an emergency exit.
- The evacuation flow rate slowed down when passengers escaped from the bus using an emergency exit. This was ascribed to the height of the emergency exit, which was thought to contribute to the difficulty in evacuation. In addition, the participants were mostly male aged between 20 and 30 years, which is the reason why the evacuation flow rate of case-8 was not slower than the other cases.
- In order to achieve a stable and continuous evacuation flow rate, the data of participants wearing the elder set were usually excluded when calculating the average evacuation flow rate. However, when focusing on the time interval between each participant, the impact of disabled participants on evacuation time did exist. This reflected that the time delay would be obvious when passengers move slowly, and a stable evacuation process would be interrupted.
- The impact of baggage on evacuation times was not clear; the baggage used in this experiment was possibly very small, so the results showed no significant difference.
REFERENCES


Fire Behaviour of Gas Spring Used in Cars

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ABSTRACT

Several accidents involving gas springs were reported by firefighters leading, in some cases, to severe injuries. This paper presents original results obtained from the study of gas spring used in car when exposed to a fire. An experimental rig was designed to assess the behaviour of gas spring in different configurations. A total of eleven tests was performed with different spring lengths, fixing modes or thermal exposure. In terms of fire safety, the aimed behaviour of a gas spring is its non-ejection thanks to an early failure of the rod seal. A sequence of events was obtained from this study highlighting the paths leading to an ejection of the gas spring by different modes: rupture of the pressure tube, “spring effect” or “missile effect”. Measurements of temperatures and forces exerted to the experimental rig were also performed and exposed in the present paper.

KEYWORDS: gas spring, fire behaviour, fire fighter safety.

INTRODUCTION

Vehicles are currently equipped with many devices under pressure such as gas spring. During a fire, the temperature rise of a gas spring results in the increase of its internal pressure which may lead to the rupture of the spring cylinder or the ejection of the piston rod out of the cylinder.

Several accidents involving gas springs were reported during fire-fighter interventions on vehicle fires sometimes leading to severe injuries. In one case, fire fighters arrived on site on a small countryside road a few kilometres away from the closest town. At their arrival, the fire involved the entire car, a new generation sedan AUDI with diesel engine. During the intervention, one of the fire fighters standing between 15m and 20m from the back of the car received the piston rod in the face after its ejection through the location of the burnt rear light. The firefighter, not protected by a face shield at this precise moment of the intervention, was severely injured and needed multiple surgeries.

During an experimental burning involving four cars parked outside (Figure 1), Renault and the Central Laboratory of Police Prefecture observed the ejection of the pressure tube of a gas spring which followed a parabolic trajectory, to end directly in the windscreen of a car parked at more than 50m (Figure 2). In this case, the pressure tube of the gas spring was not ejected through a hole but directly across the car body.
During fire investigations conducted by the Central Laboratory of the Police Prefecture, entire or part of damaged gas springs are commonly found inside the vehicle or in its close vicinity. An example which almost led to the ejection of the gas spring is visible in Figure 3. In this case, the gas spring was stuck between the roof of the car and the hatchback door. This case is very close to what was observed during the aforementioned experimental burning.
These three examples perfectly highlight the dangerousness of a violent ejection of the gas spring and the complexity of the phenomenon as two different parts or the entire gas spring (piston rod or pressure tube) were ejected. Renault group therefore decided to start a study in partnership with the Central Laboratory of Police Prefecture in order to study the fire behaviour of gas spring used in their cars and equipping most of European automobiles.

The purpose of the study was to analyse the behaviour of a gas spring when exposed to a fire. With a correct analysis of the events leading to a failure of the element, solutions would then be found to prevent any uncontrolled and unsafe behaviour of the gas spring.

HOW DOES A GAS SPRING WORK?

A gas spring is made of a rod attached to a piston moving within a sealed cylinder, named pressure tube, containing Nitrogen at high pressure and lubricant (Figure 4).

The force exerted by the spring is the result of the balance of forces on each side of the piston. As the cross section of the piston is different whether it includes the rod diameter or not, a resulting force exists pushing the rod out of the spring. A force \( F \) on Figure 5 may then be applied to the external side of the rod in order to balance or overcome the force generated by the gas spring itself. At equilibrium, Eq. (1) is verified:

\[
F + [P \times (A - a)] = P \times A
\]

(1)
With $F$ the force applied to the external side of the rod (in N), $P$ the gas pressure in the cylinder (in Pa), $a$ the rod cross section (in m$^2$) and $A$ the piston cross section (in m$^2$).

**Figure 5** Forces applied to the rod and the piston.

**EXPERIMENTAL RIG**

An experimental rig was designed to manually compress and maintain the gas spring in a compressed position. Two configurations were available to position the gas spring on the experimental rig (Figure 6):

1) using ball joint end fittings as normally installed in cars; or

2) inserting the end of the rod directly in a hole in the mounting.

**Figure 6** Two different fixation modes of the gas spring on the experimental rig.

The height of each side of the rig was adjustable in order to modify the position of the spring above the burner and to act on the inclination of the gas spring (Figure 7). It was therefore possible to maintain the lubricant on the lowest part of the pressure tube to be representative of a real situation.

The experimental rig was placed at the back of a maritime container to minimize the flame fluctuations due to external conditions and perpendicular to the length of the container to avoid any projection of the spring out of the enclosure.

The thermal stress on the gas spring was generated by a heptane pool fire. Three different sizes of fuel container were used. The objective was to expose the entire gas spring or only part of it to temperatures and radiations comparable to what exists during real vehicle fires.
A sensor measured the force exerted to the fixing points with an increase of the internal pressure in the gas spring (Figure 8). When this gauge was used, the fixing mode of the gas spring to the rig was equivalent to the insertion. During experiments, a shield was placed in front of the force sensor to stop radiations from the fire and prevent any drift due to a heating of the gauge.

Two thermocouples were placed on the gas spring to estimate the flame temperature and the thermal stress; the first one (TC-P1) was fixed on the lower part of the pressure tube and the second (TC-P2) on the upper part.

**EXPERIMENTS**

Three different sizes of gas spring were investigated for a total of eleven fire tests. All the gas springs were produced by the same manufacturer and supposed to exhibit a safe behaviour in case of fire, i.e. a rupture of the rod seal consequently decreasing the pressure inside the spring cylinder. Gas spring nominal forces ranged from 533N to 700N. All the experiments performed in this study are listed in Table 1.
### Table 1 List of performed experiments.

<table>
<thead>
<tr>
<th>Test name</th>
<th>Fixing mode (up/down)</th>
<th>Spring length</th>
<th>Nominative force (N)</th>
<th>State of compression</th>
<th>Length of fuel container</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1E1</td>
<td>Gauge/inserted</td>
<td>Medium</td>
<td>533</td>
<td>Compressed</td>
<td>Medium</td>
</tr>
<tr>
<td>S1E2</td>
<td>Gauge/inserted</td>
<td>Medium</td>
<td>700</td>
<td>Compressed</td>
<td>Medium</td>
</tr>
<tr>
<td>S1E3</td>
<td>Gauge/inserted</td>
<td>Medium</td>
<td>690</td>
<td>Compressed</td>
<td>Medium</td>
</tr>
<tr>
<td>S2E1</td>
<td>Ball joint/gauge</td>
<td>Medium</td>
<td>700</td>
<td>Compressed</td>
<td>Medium</td>
</tr>
<tr>
<td>S2E2</td>
<td>Ball joint/gauge</td>
<td>Medium</td>
<td>700</td>
<td>Compressed</td>
<td>Medium</td>
</tr>
<tr>
<td>S2EX</td>
<td>Ball joint/ball joint</td>
<td>Medium</td>
<td>700</td>
<td>Compressed</td>
<td>Small</td>
</tr>
<tr>
<td>SA</td>
<td>Inserted/inserted</td>
<td>Medium</td>
<td>690</td>
<td>Extended</td>
<td>Small</td>
</tr>
<tr>
<td>SB</td>
<td>Ball joint/ball joint</td>
<td>Long</td>
<td>610</td>
<td>Compressed</td>
<td>Long</td>
</tr>
<tr>
<td>SC</td>
<td>Ball joint/ball joint</td>
<td>Short</td>
<td>360</td>
<td>Compressed</td>
<td>Small</td>
</tr>
<tr>
<td>SD</td>
<td>Ball joint/gauge</td>
<td>Long</td>
<td>610</td>
<td>Compressed</td>
<td>Long</td>
</tr>
<tr>
<td>SE</td>
<td>Inserted/inserted</td>
<td>Long</td>
<td>610</td>
<td>Compressed</td>
<td>Small</td>
</tr>
</tbody>
</table>

### RESULTS

During the analysis of the results, it was assumed that the gas spring behaviour is not related to their pressure tube length, spring nominative force or presence of a tiny groove on the pressure tube. Observations and measurements are summarised in Table 2.

Tests are classified into four families. The **first one** gathers all the tests using insertion fixing mode on the experimental rig and no ball joint (S1E1, S1E2 and S1E3). This family allows a focus on the gas spring behaviour when it is exposed to a pool fire without considering the influence of the ball joint end fittings. Two different trends were observed:

1) **tests S1E1 and S1E3 with a rupture of the pressure tube ejecting the gas spring (tube and rod) out of the experimental rig and its insertion fixing mode (Figure 9).**
2) **test S1E2 with a failure of the rod seal and the gas spring staying on the experimental rig.**

A first conclusion is that a failure of the rod seal before the rupture of the pressure tube prevents any ejection of the gas spring or part of it. It is assumed that the rupture of the pressure tube in both tests is due to an increase of its internal pressure resulting from the increase in temperature.

![Figure 9 Comparison of medium length gas spring before and after rupture of the pressure tube.](image)

The **second family** gathers tests with a ball joint at the upper fixing point and a pressure gauge, equivalent to an insertion fixing mode, at the lower spring end (S2E1, S2E2 and SD). Two behaviours were observed:

1) a rupture of the pressure tube before a failure of the rod seal or of a ball joint (test S2E2). This behaviour is equivalent to what was described previously.
2) a failure of the upper ball joint (S2E1 and SD). The gas spring, not maintained anymore on the experimental rig, extended and was ejected from the experimental rig with a “spring effect” (Figures 10 and 11). After a visual examination at the end of the test, the rod seal was not damaged.
Table 2 Summary of main observations and measurements during experiments.

<table>
<thead>
<tr>
<th>Test name</th>
<th>Rupture time after ignition (s)</th>
<th>Rupture temperatures</th>
<th>ΔF at rupture (daN)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TC-P1(˚C)</td>
<td>TC-P2(˚C)</td>
<td></td>
</tr>
<tr>
<td>S1E1</td>
<td>66</td>
<td>275</td>
<td>185</td>
<td>78</td>
</tr>
<tr>
<td>S1E2</td>
<td>215</td>
<td>530</td>
<td>215</td>
<td>190</td>
</tr>
<tr>
<td>S1E3</td>
<td>235</td>
<td>505</td>
<td>410</td>
<td>165</td>
</tr>
<tr>
<td>S2E1</td>
<td>113</td>
<td>255</td>
<td>255</td>
<td>75</td>
</tr>
<tr>
<td>S2E2</td>
<td>98</td>
<td>340</td>
<td>375</td>
<td>80</td>
</tr>
<tr>
<td>S2EX</td>
<td>290</td>
<td>535</td>
<td>406</td>
<td>N/A</td>
</tr>
<tr>
<td>SA</td>
<td>321</td>
<td>400</td>
<td>100</td>
<td>N/A</td>
</tr>
<tr>
<td>SB</td>
<td>105</td>
<td>180</td>
<td>265</td>
<td>N/A</td>
</tr>
<tr>
<td>SC</td>
<td>125</td>
<td>245</td>
<td>265</td>
<td>N/A</td>
</tr>
<tr>
<td>SD</td>
<td>103</td>
<td>110</td>
<td>295</td>
<td>77</td>
</tr>
<tr>
<td>SE</td>
<td>115</td>
<td>290</td>
<td>45</td>
<td>N/A</td>
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</table>

Figure 10 Damaged tube end fitting after fire exposure and impact in the wall of the enclosure.
Figure 11  Entire gas spring ejected and stuck on the left-hand side of the enclosure.

It appears that a failure of the ball joint while the gas spring is still compressed leads to a relatively violent ejection of the entire spring out of the experimental rig if it is not maintained by a ball joint at the other end. A longer heating of the spring before the failure of the ball joint may lead to an even more violent ejection due to a higher internal pressure in the cylinder.

The third family gathers experiments with a ball joint at each end of the gas spring (S2EX, SB and SC). For all these tests, a failure of a ball joint (or both) was observed before a failure of the rod seal or a rupture of the pressure tube. The failure of the ball joint led to three different behaviours:

1) failure of the rod end fitting resulted in the extension of the rod which was then resting on the heptane container (S2EX). The gas spring and the second ball joint were consequently still exposed to the pool fire. When the tube end fitting failed in its turn, the gas spring lied on the fuel container. This new configuration was equivalent to an uncompressed gas spring directly exposed to the fire. The rod seal finally failed. The lubricant and high pressure gas exhausting towards the heptane container created a fire ball. However, this phenomenon did not lead to the ejection of the gas spring. These observations are close to those obtained from test S1E2.

2) failure of the tube end fitting (SB and SC). The sequence of events is then identical to what was previously described for tests S2E1 and SD, except that the rod was maintained by a ball joint and not only inserted in the mounting of the experimental rig.

During SC test, the rod end fitting failed leading to the extension of the gas spring and, consequently, its ejection from the experimental rig. Conclusions are identical to what was obtained for S2E1 and SD and the described “spring effect”.

For SB test, the ball joint did not fail during the extension of the gas spring leading to a split of the rod and the pressure tube. The ejection by “spring effect” was then combined to a “missile effect” with the exhaust of the pressurised gas and the ignition of the lubricant contained in the spring (Figure 12). The kinetic energy of the spring at the ejection was higher than in other configurations.
The *last family* gathers tests where the gas spring was installed with insertion fixing mode and only exposed to the fire in the surroundings of the rod seal (SA and SE). These tests were performed to verify that a rapid failure of the rod seal with little or no damage on ball joints or pressure tube did not lead to the ejection of the gas spring. This hypothesis was verified with the gas spring compressed (rod in the pressure tube - SE) and extended (rod outside the pressure tube - SA).

For both configurations, the rod seal failed after 321s and 115s following ignition for, respectively, tests SA and SB. It resulted from this failure an exhaust of gas and lubricant contained in the spring cylinder but without any ejection of the gas spring or projection of any part of it (Figure 13).

**MEASUREMENTS**

Temperature and force variations measurements for tests S1E1, S1E2 and S1E3 are plotted.
respectively in Figures 14 and 15. A rupture of the pressure tube was obtained for tests S1E1 and S1E3 whereas a failure of the rod seal was observed for test S1E2. The ruptures of the pressure tube were reached for very different temperatures: 275°C and 185°C for S1E1 against 505°C and 410°C for S1E3. The gap between force variations was also important with respectively 78daN and 165daN at rupture. It is assumed that these differences may be due to the spring nominative forces (533N for S1E1 and 690N for S1E3).

However, the rod seal failure in test S1E2 happened at temperatures and force variation close to S1E3: 530°C measured at TC-P1, 215°C at TC-P2 and a force variation of 190daN. The force variation is directly related to the increase in pressure in the gas spring cylinder.

It is consequently not possible to predict the spring behaviour when exposed to a fire based on temperature or pressure increase thresholds. This conclusion is verified on the eight other experiments. A reason may be the slight differences existing in gas spring length or nominative force. It may also better be explained by a non-uniform thermal stress as the flames from the pool fire oscillate and do not expose the gas spring to a constant heat flux. In future experiments, this particular point would be improved by the use of a sand burner or liquid fuel container with lower rims.

---

**Figure 14**  Temperature measurements (°C) as a function of time (s) for S1E1, S1E2 and S1E3 tests.

**Figure 15**  Force variation measurements (daN) as a function of time (s) for S1E1, S1E2 and S1E3 tests.
CONCLUSIONS

A sequence of events is summarised in Figure 16. Consequences of the test are organised according to a decrease of their seriousness:

\[
\text{Ejection of the gas spring with a "missile effect" } > \text{ ejection of the gas spring with "spring effect" } > \text{ ejection of the gas spring with rupture of the pressure tube } > \text{ no ejection of the gas spring}
\]

It is considered that the only safe configuration for fire fighters is when no ejection of the gas spring is observed.

\[\text{Figure 16  Sequence of events during experiments – figures above the arrows correspond to the number of experiments for each path. If no failure of the ball joint, this fixation mode is assumed to be equivalent to the insertion mode.}\]

A solution to avoid any violent phenomenon is a quick failure of the rod seal before a rupture of the pressure tube or a failure of a ball joint. A reinforcement of the ball joint to prevent any failure may lead in given conditions to an undesired rupture of the pressure tube before the failure of the rod seal and the release of gases contained in the cylinder.

It is not possible to relate the temperature or the force measurements to a given behaviour of the gas spring i.e. rupture of the pressure tube, early failure of the rod seal or ejection of the gas spring.

To predict the behaviour of a compressed gas spring during a fire, some manufacturers expose its rod seal to a Bunsen burner flame. The localised thermal exposure induced by such flame is very different from what was obtained when the entire gas spring. Its mounts were engulfed in flames. A localised exposure does not take into account issues related to an early failure of ball joint or the increase in the cylinder pressure leading to a rupture of the envelop before a failure of the rod seal.

These results were exposed to a gas spring manufacturer which will take into account exposed issues in the development of their future products. This study will consequently improve the safety of fire-fighters in European countries.
Statistical Analysis, a Need to Reach an Optimised Risk Management in Car Parks

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ABSTRACT

This paper deals with the evolution and the increase of fire hazard in car parks through the years. The main objective is to follow this evolution. Analysis of data proves that a statistical approach is necessary to complete risk management tools, especially to justify the adequacy between fire prevention/protection means and cost.

A statistical study was recently conducted in the context of a French working group in charge of updating French car parks regulation.

First of all, the results of this recent study is compared with a survey performed 20 years ago.
Then, fire risk in car park is presented macroscopically through a study of one of the most important fire that happened last year in a French car park. Firefighting difficulties on this type of disaster are described by the firefighter’s feedback.
Finally, new car technologies issues are detailed by a focus on electric and hydrogen vehicles.

KEYWORDS : car parks, statistical study, fire risk, fire safety regulation

INTRODUCTION AND CONTEXT

Studies of fires in car parks are a large concern all around the world [1][2][3]. The fire risk associated with car parks is particularly difficult to consider regarding the numerous influencing factors and issues (firefighters action, attendance of parking lots and type of vehicles, evacuation of people, control of fire spread, smoke movement, management of ventilation, structural fire behavior, etc.) [4]. Considering the complexity of the risk involved in this kind of fire, a statistical approach can provide valuable information and feedback on good/bad practices.

The study highlights the complementarity of a statistical approach with the determinist one commonly used to demonstrate risk compliance.
In addition, this approach gives a first feedback on influencing factors and on the efficiency of fire risk control measures. This may be used to improve them in order to define efficient and optimized solutions regarding economical aspect and constraints of operators/users. It also drives the fire scenarios used by fire safety engineers at design phase [5][6].

The statistical study presented in this paper has been carried out by Efectis in the context of a project led by Ministry of the Interior – Civil Defense (DGSCGC) and involving members from Paris Fire brigade, the National Federation of car parks operators (FNMS) and the National chamber of the Architects.

Data has been collected on analysis of causes and consequences of fire events that occurred in car parks. 200 different inputs have been considered for each fire/car park. They were related to the
parking lot (number of places, etc.), fire characteristics (date, time, number and type of vehicles involved, etc.), fire risk means (alarm, compartmentation, smoke extraction, etc.), victimology (persons injured, fatalities, etc.), firefighters actions (time to reach the scene, delay for control, means used, etc.) and financial aspect (operating loss, rehabilitation, fire risk means, etc.). The 200 inputs have been filled at an average rate of 12-13%.

All these data are compared to the statistical information recorded from a less detailed survey of fire in car parks performed 20 years ago [7]. This comparison assesses the evolution of fire risk in car parks.

On top of that, an important car park fire that recently occurred in France is analysed and the feedback of firefighters is presented to highlight main difficulties.

Nowadays, no statistics are available to analyse, by a quantitative approach, the emerging risks associated to new technologies. For this reason, and to take into account this new kind of risk, a presentation of main fire tests realised on electric and hydrogen vehicles is included in this paper.

FIRES IN CAR PARKS EVOLUTION THROUGH THE YEARS – STATISTICAL APPROACH

Statistical studies enable to define trends with the valorization of data collected. In this part of the document, a comparison of figures between two studies (realized with less than 20 years of interval) is used in order to highlight the evolution of fire risk in car parks through the years.

Data presentation

- **Statistical study realised in 2015**

Table 1 presents a general view of data collected for the statistical study previously introduced.

<table>
<thead>
<tr>
<th>Number of car parks studied</th>
<th>1931 (41 % with a fire / 59 % without a fire)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dates of fires</td>
<td>92 % of recorded fires between 2010 and 2014</td>
</tr>
<tr>
<td>Type of car parks</td>
<td>- Underground : 78 %</td>
</tr>
<tr>
<td></td>
<td>- Upper-structure (representative of open car parks ) : 13 %</td>
</tr>
<tr>
<td></td>
<td>- Mix (underground and upper-structure) : 9 %</td>
</tr>
<tr>
<td>Data sources</td>
<td>- Ministry of the Interior – Civil Defense (DGSCGC) : 55 % (without data of fire)</td>
</tr>
<tr>
<td></td>
<td>- Fire brigades from all over France (SDIS) : 36 % (represents 78 % of fire data)</td>
</tr>
<tr>
<td></td>
<td>- National Federation of car parks operators (FNMS) : 6 % (represents 15 % of fire data)</td>
</tr>
<tr>
<td></td>
<td>- Paris Fire brigade (BSPP) : 2 % (represents 5 % of fire data)</td>
</tr>
<tr>
<td></td>
<td>- Civil Protection daily newsletter (BQPC) : 1% (represents 2 % of fire data)</td>
</tr>
</tbody>
</table>

An important quantity of data concerning fire in car parks or only characteristics of car parks (without fire) have been collected from car parks operators and fire brigades.
### Statistical study realised in 2000

A quick presentation of data collected in the field of this study is presented in Table 2.

**Table 2  Data collected in data base – Statistical study of 2000**

<table>
<thead>
<tr>
<th>Number of car parks</th>
<th>405 (100 % with a fire)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dates of fires</td>
<td>100 % of recorded fires between 1995 and 1997</td>
</tr>
<tr>
<td>Type of car parks</td>
<td>Underground: 80 %</td>
</tr>
<tr>
<td></td>
<td>Upper-structure (representative of open car parks): 20 %</td>
</tr>
<tr>
<td>Data sources</td>
<td>Paris Fire brigade (BSPP)</td>
</tr>
</tbody>
</table>

Data concerning fire in car parks have been collected from Paris Fire brigade only but confirmed with limited data from Berlin and Marseille.

### Results and trends

This chapter presents the results of the 2015 statistical study and uses the comparison with the results of the 2000 study [7] in order to highlight some trends of evolution concerning fire hazards in car parks.

**Important influencing factors on fire occurrence**

This part only concerns data of 2015 statistical study. Some figures enable to understand the fire risk in a life of a car park.

For example the probability that a fire occurs during car park lifetime is closed to 1 (about 5000 fires in 30 years) and the probability that two fires occur in the same car park is not nil.

As shown by Figure 1, probability of occurrence of a fire can be directly related to the population density in the area where car parks are located (main cities).

![Figure 1  Correlation between number of fires in car parks and population density](image)

The probability that a fire occurs in a car park with more than 1000 places (12 % of car parks) is 6 times greater than in a car park with less than 1000 places (Figure 2).
Another factor is the increasing of activities in car park area. Statistics show that 32% of car parks contain an activity. The most frequent ones are indicated in Figure 3. It represents different kinds of risk and an additional source of ignition.

- **Ignition, occurrence and severity of fire**

Evolution of “the reference car parks fire” is defined by Table 3.

**Table 3 Characteristics of a fire in car park**

<table>
<thead>
<tr>
<th></th>
<th>Statistical study of 2015</th>
<th>Statistical study of 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ignition by car</strong></td>
<td>- Car : 61 %</td>
<td>- Car : 68 %</td>
</tr>
<tr>
<td></td>
<td>- Detritus : 20 %</td>
<td>- Others : 32 %</td>
</tr>
<tr>
<td></td>
<td>- Electric origin (including technical area): 5 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Others : 15 %</td>
<td></td>
</tr>
<tr>
<td><strong>Cause of ignition</strong></td>
<td>- Arson : 60 %</td>
<td>- Technical problem : 20 %</td>
</tr>
<tr>
<td></td>
<td>- Technical problem : 20 %</td>
<td>- No-determined : 20 %</td>
</tr>
<tr>
<td></td>
<td>- No-determined : 20 %</td>
<td>No data</td>
</tr>
<tr>
<td><strong>Day time of the ignition</strong></td>
<td>40 % between 21 h and 6 h with a decrease between 2 h and 8 h (Figure 4)</td>
<td>Same trend than in study of 2015</td>
</tr>
</tbody>
</table>
The statistics show that the cause of ignition, the day time of occurrence and the proportion of fires involving cars are constant though the years. However, the number of cars involved increases which implies that the severity of fire increases by the same way.

Concerning the localization of the fire, the probability that it occurs at R-1 level is 5 times greater than at level R-5 or R-6. This trend is highlighted by the Figure 5. This trend shows that fire occurring is most frequent at the level where the vehicles turnover frequency is high (vehicles turnover is most important at levels close to the access/exit levels, often located at R-0 or R-1).

The probability indicator of occurrence is defined by the following equation.

\[
\text{Indicator}(\text{level _}_X) = \frac{\text{Number of fires at level _}_X}{\text{Number of car parks which contain the level _}_X} \times 100
\]

- **Firefighters action**

Evolution of firefighter’s action is described by the following figures presented in Table 4.
Table 4 Some figures about fire fighters action

<table>
<thead>
<tr>
<th></th>
<th>Statistical study of 2015</th>
<th>Statistical study of 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of mobilized</td>
<td>More than 20 : 50 % of fires</td>
<td></td>
</tr>
<tr>
<td>fire-fighters</td>
<td>More than 40 : 20 % of fires</td>
<td></td>
</tr>
<tr>
<td>Time between alert and</td>
<td>Average : 7 minutes</td>
<td>No data</td>
</tr>
<tr>
<td>arrival of fire-fighters</td>
<td>Maximum : 24 minutes (97,5 % cover by 15 minutes)</td>
<td></td>
</tr>
<tr>
<td>Activation time (to</td>
<td>Average : 12 minutes</td>
<td></td>
</tr>
<tr>
<td>reach the fire source)</td>
<td>Maximum : 2 hours (98,5 % cover by 1 hour)</td>
<td></td>
</tr>
<tr>
<td>Extinction time</td>
<td>Less than 60 minutes: 40 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 90 minutes: 58 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Above 120 minutes: 30 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum : 10 hours (10 % above 4 hours)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 60 minutes: 95 % in 1997</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 90 minutes: 98 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Above 120 minutes: 0,6 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum : 4 hours</td>
<td></td>
</tr>
</tbody>
</table>

These data confirm the evolution of fire severity through the years.

- **Fire risk means**

Main fire risk protection means used in car park are presented below in Table 5.

Table 5 Main fire risk means - Statistical study of 2015

<table>
<thead>
<tr>
<th>Means of smoke extraction</th>
<th>Current situation</th>
<th>Efficiency in fire situation*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mechanical : 67 %</td>
<td>30 % of dysfunction (system off, system equipment overheat due to the fire, no efficient design)</td>
</tr>
<tr>
<td></td>
<td>Natural : 23 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mix (mechanical and natural) : 10 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fire extinguisher system</th>
<th>Current situation</th>
<th>Efficiency in fire situation*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Car parks equipped : 15 %</td>
<td>25 % of dysfunction</td>
</tr>
<tr>
<td></td>
<td>All levels covered : 80 % (the others not covered 20 % concern levels at proximity of access/exit levels)</td>
<td></td>
</tr>
</tbody>
</table>

* based on limited information

These observations show the importance of a well-adapted design and a regular maintenance.

- **Injury and fatality**

Even if fire risk in car park is not a critical problem for evacuation, some cases of injury and fatality have been recorded.

Table 6 Injury and fatality due to fires in car parks

<table>
<thead>
<tr>
<th></th>
<th>Statistical study of 2015</th>
<th>Statistical study of 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injured people</td>
<td>- 91 injured persons in total</td>
<td>- 13 injured persons in total</td>
</tr>
<tr>
<td></td>
<td>- A maximum of 8 injured persons during the same fire</td>
<td>- A maximum of 2 injured persons during the same fire</td>
</tr>
<tr>
<td></td>
<td>- Most people injured are firefighters</td>
<td>- Most people injured are firefighters and first intervention people</td>
</tr>
<tr>
<td>Fatality</td>
<td>3 death in total</td>
<td>No fatality</td>
</tr>
</tbody>
</table>
Extra information about these cases of fatality are:
- a homeless person which has been discovered below the stairs of impacted car park,
- a person in cardiac arrest which has been discovered in his bed in habitations above the car park (probably spread of smokes by canalisations or other smoke vector spread),
- a non-detailed case.

MACROSCOPIC EVOLUTION OF FIRE HAZARDS

To combine statistic and determinist approaches, feedbacks of main car park fires are described in this chapter. One of the most important fire that recently occurred in France is analyzed. Main problems encountered by firefighters are developed and new car technologies are described to highlight the new type of fire hazards.

Analysis of fire risk

- **Edouard VII fire**

<table>
<thead>
<tr>
<th>Car park characteristics</th>
<th>Statistical study of 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Underground levels : 4 (with 2 half levels by level)</td>
<td></td>
</tr>
<tr>
<td>- Surface by level : 3 150 m²</td>
<td></td>
</tr>
<tr>
<td>- Number of places : 503</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fire risk means</th>
<th>Fire strength : 41 cars destroyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Mechanical smoke exhaust</td>
<td></td>
</tr>
<tr>
<td>- Three dry column serving all levels</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fire consequences</th>
<th>- Injured : 6 fire fighters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Building structure : lifting of the suspended ceiling tile</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strengths of the management of fire disaster</th>
<th>- Fire risk means of car park : mechanical smoke extraction to manage smoke spread</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Firefighting action : use of foam for extinction</td>
</tr>
</tbody>
</table>

| Weaknesses in management fire disaster | First deployment equipment and recognition operation not enable to attack the fire source (due to the no efficient information transmitted by security staff of car park). This weakness leads to an activation time (to reach the fire source) of 2 hours. |

In this case, the problem was the time needed for firefighters to reach the fire source. This delay enabled an important fire spread in one entire level. This problem is in part due to the incorrect information given by the park staff to the firefighters. After an activation time of 2 hours, it was very difficult for firefighters to extinguish fire and secure the situation.

- **Main problems for firefighters**

In the field of the work project led by French Ministry of the Interior, Paris Firefighting Brigade (BSPP) presented main problems encountered by firefighters during intervention.

Interventions are difficult because of:
- An important smoke spread (decrease of visibility) in all car parks (staircase used for intervention, etc.) which implies a difficulty to localize the fire source on top of the complexity of the spatial arrangement,
- A rapid fire spread caused by the proximity of combustibles, lightweight walls and various crossing wall like ventilation conducts and pipes,
- A risk of structural collapse because of the fact that structures are not design to resist of such heat stress in underground car parks (temperature exceeds the ISO curve that defines standard thermal actions),
- A high temperature due to the compartmentation reducing the capabilities to reach the
fire source even with firefighter protection (resists to a heat flow of 40 kW/m² during 5 minutes),
o The necessity to secure staff of car park and evacuate users.

New technologies, new fire hazards

Car fire test campaigns have been performed in Europe since twenty years [2] [9] and other fire tests were organized in 2014 and 2015 in particular by SDIS 44 [11].

In addition of the fact that the risk increases with new equipments in recent cars (increase of fire load), the new technologies also create new fire hazards.

Following chapters describe new technologies of electric and hydrogen vehicles in this field.

- **Electric vehicle**

Main problematic of fire risk for electric vehicles is the thermal runaway of batteries and it depends on configuration, technology of batteries and protection means of the vehicle.

If thermal runaway is avoided, consequences of fire are close to a thermal vehicle. Nevertheless in case of thermal runaway, consequences are projections of metal in fusion and exhaust of electrolyte liquid implying violent thermal phenomena. These effects lead to an acceleration of fire spread to the fire loads at proximity.

Some scientific researches are realised on the subject of thermal runaway. In the document [8], a work carried out on lithium-ion batteries technology is presented. Thermal runaway is due to an overheating of batteries which creates an exothermic reaction in the cells. If the energy created by the exothermic reaction cannot be dissipated, a rapid increase of temperature occurs.

Then thermal stress and augmentation of pressure due to the rapid increase of temperature lead to a break of one battery cell. Consequences are a localized high temperature and a rapid discharge of energy due to the localized explosive atmosphere created. This implies an increase of the adjacent cells temperature which creates a cell-to-cell cascading thermal runaway. During this phenomenon, the energy release increases.

Tests indicates a thermal runaway for a duration of 5 minutes that occurs approximately one hour after fire ignition.

Metal fire (lithium, etc.) implies that traditional equipment of firefighters are not efficient to extinguish the fire. In fact, reaction occurs without oxygen and creates its own energy and an electrolyte combustible. Projection of water on the kind of fire leads to produce hydrogen.

On top of the potential projections of metals in fusion, the localized high temperatures are dangerous for firefighters. As mentioned in [10] toxic and corrosive products are created and released with the effluents.

This new fire hazard creates a challenge to find efficient solutions of risk preventing/protection. [8] describes a solution that consists in an injection of dielectric fluids before or after the beginning of thermal runaway to avoid the cell-to-cell cascading thermal runaway. This injection enables to dissipate the heat energy which is the spread mode of thermal runaway.

Statistical study of 2015 shows the importance of this new technology evolution in car parks by the numbers of electric vehicle charging stations (Figure 6).
• **Hydrogen vehicle**

On top of the risk of thermal runaway of batteries, the main problematic of hydrogen vehicles is explosion of the high pressurized tank of hydrogen.

Hydrogen is stocked in a high pressure tank at about 300 bars (up to 700 bars). To avoid an explosion in case of overheating due to a fire, a thermal rupture disc is installed in the high pressurized tank. Nevertheless, in case of fire, the pressure in the tank increases of dozens of bars before the rupture of the thermal disc. At this moment all the hydrogen is removed of the tank and is consumed by the fire. Consequence is close to a thermal heating of an important jet fire all around the tank of hydrogen until all hydrogen is consumed. Temperature exceeds 1000 °C, concrete spalling of structure and the fire spread to the other fire loads cannot be avoided.

This phenomenon is a real problem for firefighters because of this instantaneous phenomenon and the hot effluents propagation.

**CONCLUSION AND PERSPECTIVES**

The work presented in the present paper enables to show the evolution of fire hazards in car parks.

The analysis leads to conclude that fire hazard in car parks increases a lot in 20 years with the evolution of activities and the new car technologies. That’s the reason why it is important to follow this risk with quantitative figures that enable to be aware of the evolutions and consequently to optimize fire means protection. Statistical studies appear to be the most appropriated way to complete the deterministic approach.

In order to reach an efficient balance between risk management, costs and operation constraints, it is necessary to verify the impact of regulatory changes on the fire risk. Statistical approach has to be developed in the future with a standardized method.

In the context of the French underground car parks regulation upgrade and as a perspective, it is suggested to develop a tool with an interactive database of fire in car parks.

**REFERENCES**

4. ANON. Car parks in fire. SteelConstruction.info - http://www.steelconstruction.info/Car_parks_in_fire
7. D. JOYEUX, L-G CAJOT, P. VAN DE LEUR. FINAL REPORT “Demonstration of real fire tests in car parks and high buildings CE” - agreement 7215 - PP/025-
10. INERIS, RAPPORT D’ÉTUDE 06/06/2011 DRA-10-111085-11390D - Approche de la maîtrise des risques spécifiques de la filière véhicules électriques.
Analysis of Energy Release during Thermally-induced Failure of Lithium Ion Batteries: Implications for Vehicle Fire Safety

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ABSTRACT

With the increasing need and popularity of lithium ion batteries (LIBs), it is important to quantify and compare the dynamics and energetics of the thermally-induced failure of LIBs based on different chemistries. This practice is expected to lay a foundation for fire safe design of the energy storage systems utilizing LIBs, including those employed in ground vehicles. In the current study, a new experimental technique, Copper Slug Battery Calorimetry (CSBC), was employed for the quantitative analysis of thermal failure of cylindrical LIB cells of identical geometry containing three different cathode chemistries: lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP). The thermal transport properties of these cells were measured and the energy released both inside and outside the cells upon their thermal failure was quantified using a combination of experiments and physics-based modeling. The CSBC technique was coupled with cone calorimetry to evaluate the energy released outside the cells through flaming combustion of vented battery materials. The energy generated inside the cells was found to increase non-linearly with increasing amount of electric energy stored in an LIB. Among the battery chemistries investigated, the LCO LIBs were found to release the highest amount of energy internally, 37.3±3.3 kJ per fully charged cell, while the LFP LIBs were found to be the least energetic, 13.7±0.4 kJ per fully charged cell. The energy released during flaming combustion (outside the cells) did not show a clear dependence on the stored electric energy. The combustion energy release by each cell varied between 35 and 63 kJ/cell for LCO LIBs, 27 and 81 kJ/cell for NMC LIBs, and 36 and 50 kJ/cell for LFP LIBs. Work is underway to demonstrate how results of these measurements can be employed to predict cascading failure of multi-cell assemblies representing battery packs.

KEYWORDS: Lithium ion battery; Cathode materials; Thermal runaway; Fire safety; Copper Slug Battery Calorimetry; Cone calorimetry

1. INTRODUCTION

With the optimal combination of energy density, efficiency, cycle life and minimal memory effect [1], lithium ion batteries (LIBs) are the state-of-the-art energy storage devices and have been adopted in a wide variety of electrical and electronic systems. When LIBs are subjected to environmental conditions outside their intended design envelope, they may fail irreversibly. More specifically, when exposed to excessive external heat, unintended exothermic reactions may be initiated. These reactions take place within and between the four primary components of an LIB: the anode (most commonly carbon), the cathode (typically, a lithium metal oxide), the electrolyte (lithium salt dissolved in a mixture of organic carbonates) and the separator (a thin layer of porous polymer). These reactions can produce a large amount of thermal energy at an increasing rate. At an early stage, these reactions are accompanied by venting of potentially combustible gases and aerosols; this stage is referred to as “safety venting” [1]. At a later stage, the battery can self-heat rapidly, while simultaneously ejecting a portion of the anode and cathode materials; this stage is usually referred to as “thermal runaway” [1, 2].
Quantification of the dynamics and energetics of both stages of the failure process is necessary to understand the safety impact of various lithium ion cell and pack designs. Considerable research efforts have been dedicated to understanding energetics of the thermally-induced failure of LIBs. Differential scanning calorimetry (DSC) was used to study a number of electrode and electrolyte materials as well as their combinations. Yang et al. [3] employed DSC to investigate the most common anode material, graphite, at various states of charge (SOC). A sharp exothermic peak was detected at high temperature when samples contained more than 0.71 lithium ions per 6 carbon atoms. Maleki et al. [4] utilized DSC to examine the thermal stability of the graphite/LiCoO₂ battery chemistry. It was found that the total exothermic heats of decomposition for the anode (graphite) and cathode (LiCoO₂) were 697 J g⁻¹ and 407 J g⁻¹, respectively, and these heats decreased by about 60% with the removal of electrolyte (a mixture of organic carbonates and LiPF₆).

Von Sacken and co-authors [5] employed accelerating rate calorimetry (ARC) to show that a carbon intercalation anode material was superior to a lithium metal anode from the aspect of thermal stability. Recently, Walters and Lyon [6] used a bomb calorimeter (pressurized with nitrogen to exclude the heat produced in flaming combustion) to evaluate the total heat released during LIB failure. They found that for fully-charged T-Energy ICR18650 cells, which were also examined in the current study, the total heat was about 60 kJ/cell.

In this work, a recently developed experimental technique, Copper Slug Battery Calorimetry (CSBC) [7], was utilized to investigate the thermally-induced failure of 18650 form factor commercial LIBs representing a range of cathode chemistries including lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP). Some of the results presented here for NMC cells were reported in an earlier publication [7]. These results are repeated to provide a comprehensive comparison between the battery types.

The stand-alone version of the CSBC apparatus was used to measure the heat capacity of the LIB cells and to quantify the rate of heat generation inside the cells during the thermally-induced failure process. A computer model was constructed within the COMSOL Multiphysics environment [8] to simulate the heat transfer processes associated with the CSBC experiments. This model was used to elucidate thermal conductivities of the batteries and validate key assumptions employed in the calculation of the internal heat generation rate. In separate experiments, CSBC was combined with cone calorimetry [9] to determine the heat released in flaming combustion of the materials ejected from the battery. Together with the stand-alone CSBC experiments, these measurements provided a comprehensive evaluation of the energetics of the failure process and impact of SOC and cathode chemistry on this energetics.

2. METHODS

2.1 Sample Preparation
The three types of LIB cells analyzed in this study were T-Energy ICR18650 (LCO) [10], Panasonic CGR18650CG (NMC) [11], and K2 18650E (LFP) [12]. LCO cells consist of lithium cobalt oxide cathode, carbon anode and have nominal capacity of 2,600 mA h; NMC cells consist of lithium nickel manganese cobalt oxide cathode, carbon anode and have nominal capacity of 2,250 mA h; and LFP cells consist of lithium iron phosphate cathode, carbon anode and have nominal capacity of 1,500 mA h. It should be noted that, while the main difference between the cells was the chemical structure of the cathode, other differences in structure and composition were likely to be present (due to the commercial nature of the tested specimens) and may have contributed to the observed differences in the cell’s thermal performance and failure dynamics.

Prior to each experiment, the cell’s plastic packaging was stripped off and it was charged to a specific state of charge (SOC) with an iCharger 208B using the constant current/constant voltage method. The selected SOCs were 0, 25, 50 and 100%. The electrical energy stored in the batteries ranged from 0 to 32.8 kJ, 0 to 27.0 kJ and 0 to 15.8 kJ for LCO, NMC and LFP cells, respectively. Due to the differences in the cathode chemistry, different cell types had significantly different electric capacities. Therefore, to provide adequate comparisons, the key quantities describing the failure process are presented in this manuscript as a function of the stored electrical energy (kJ), rather than SOC.
2.2 Copper Slug Battery Calorimetry

A schematic of the CSBC apparatus is shown in Figure 1. The primary component of the CSBC is a hollow cylinder (or slug) composed of nearly pure (99.5%) copper. This slug houses an LIB specimen. The top surface of the specimen is leveled with the upper edge of the slug so that the cell’s safety vent ports are open to the atmosphere. The internal dimensions of the slug ensure a good thermal contact with 18650 form factor LIBs. An electric heater consisting of a resistive heating wire (OMEGA NI80-010-200) insulated with 3M Ruban Isolant tape is tightly wrapped around the slug. This heater is used to initiate the failure process. It is powered by a DC power supply, BK Precision 1685B, employed in a controlled power mode.

The copper slug is housed inside a larger cylinder that consists of Gemcolite FG23-112HD ceramic fiber thermal insulation, which is used to minimize heat losses from the system to the environment. The temperature of the slug is monitored with an embedded type K thermocouple. This temperature is read at a frequency of 1 Hz by a data acquisition module (DAQ) and recorded as a function of time by a computer.

Under the assumptions that the slug and sample LIB can be treated as a lumped heat capacity system and that the kinetic energy of ejected battery materials is negligible, the energy conservation statement describing the CSBC experiment can be written as follows

\[
\text{loss} + P_{\text{IN}} + P_{\text{LIB}} = c_{\text{slug}} m_{\text{slug}} \frac{dT_{\text{slug}}}{dt} + c_{\text{LIB}} m_{\text{LIB}} \frac{dT_{\text{LIB}}}{dt} + P_{\text{loss}}
\]

(1)

In this statement, \( P_{\text{IN}} \) is the electric power supplied to the heater; it was kept at 20 W for the duration of all experiments on LIBs. \( P_{\text{LIB}} \) is the power of heat generation by the thermal failure processes inside the battery. It is the sought after quantity, which is a function of time, \( t \). The first term on the right hand side is the sensible heat change of the slug expressed in terms of its heat capacity \( (c_{\text{slug}}) \), mass \( (m_{\text{slug}}) \) and temperature \( (T_{\text{slug}}) \). The heat capacity of the slug is equal to that of copper [13]; the mass of the slug is also known. The second term on the right hand side is the sensible heat change associated with an LIB cell expressed in terms of the battery’s heat capacity \( (c_{\text{LIB}}) \) and mass \( (m_{\text{LIB}}) \).

The last term, \( P_{\text{loss}} \), represents the rate of thermal energy transfer from the slug and battery specimen to the insulation and ambient air.

First, \( P_{\text{loss}} \) and \( c_{\text{LIB}} \) were carefully quantified using a set of procedures detailed in a previous publication [7]. Subsequently, 10 CSBC tests were conducted on each battery type at each SOC to determine \( m_{\text{LIB}} \) and \( P_{\text{LIB}} \) and accumulate statistics. In addition, 3 CSBC tests for each battery type were carried out where a stainless-steel-sheathed thermocouple probe was placed inside a fully discharged LIB. The probe was inserted through a 1.6 mm diameter orifice drilled in the bottom of the battery casing and positioned on the axis of the LIB with the thermocouple bead located 20 mm away from the top of the casing (the same level as the bead of the copper slug thermocouple). These
temperature measurements, recorded as a function of time, were utilized to examine heat transfer within the LIB and interpreted using numerical modeling.

2.3 Numerical Modeling

A numerical model of the CSBC experiments was constructed using the COMSOL Multiphysics software [8]. The CSBC apparatus was represented by an axisymmetric object as shown in Figure 2. The dimensions of the key object elements were defined to match those of the actual apparatus. A temperature-dependent convection coefficient was prescribed to capture free convective cooling of the outer walls of the apparatus. Based on a well-established empirical correlation [14], the value of this coefficient was set to increase from 7.5 to 14.4 W m⁻² K with temperature increasing from 298 to 800 K. The environmental temperature was maintained at 298 K.

![Figure 2](image)

Radiative losses from the outer walls to the environment were defined using the broadband emissivity of 0.50, 0.78 and 0.80 for the LIB, copper slug and insulation surfaces, respectively. The LIB surface emissivity was set to be equal to that of partially oxidized steel [15]. The slug emissivity was set to be equal to that of copper oxide [15] (due to the apparent presence of the oxide on the outer surface of the slug after only a few thermal cycles). The emissivity of the insulation was set to be equal to that of ceramic [15] (due to similarity in composition).

The density, heat capacity and thermal conductivity of all copper elements were defined using available literature data [13, 15]. The density of the insulation was measured and defined to be 350 kg m⁻³. The insulation’s heat capacity was computed from its known composition, 55 wt.% SiO₂ and 45 wt.% Al₂O₃, and literature data [13]. The electrical heater was simulated by distributing the supplied electrical power in a form of heat at the outer surface of the copper slug. The numerical simulations were conducted using “extremely fine” mesh option (characteristic element size of ≈0.6 mm). The time step was set at 0.2 s. Decreasing or increasing this time step by a factor of 5 did not change the results of the simulations, indicating convergence.

Initially, simulations of the $P_{\text{loss}}$ calibration tests [7] (where an LIB was replaced by a solid copper cylinder) were carried out. These simulations were used to determine the thermal conductivity of the insulation material, which was the only undefined parameter, by matching simulated and experimental copper slug temperatures. The thermal conductivity that increases from 0.065 to 0.15 W m⁻¹ K⁻¹ with temperature increasing from 298 to 800 K provided a good agreement (within 5% in K) between all simulated and experimental data.

Subsequently, the thermal conductivities of the LIB cells were determined using a similar inverse modeling approach. The cells were assumed to be isotropic cylinders defined by experimentally determined density and heat capacity. The axial probe temperature experimental histories, which were collected only up to the onset of safety venting, were matched by the model through adjustment of the LIB conductivity values.
Finally, using derived insulation and LIB thermal transport properties, a validation of the experimentally determined $P_{IHG}$ temporal profiles was carried out by performing simulations where these profiles were prescribed as a piecewise-linear volumetric heat generation function and applied to the LIB volume. The simulated slug temperatures were compared to the experimental data. In these simulations, the LIB density was defined as a function of time, which was calculated from the corresponding linearly interpolated experimental $m_{LIB}$ data.

2.4 Cone Calorimetry

In the final experimental series, the CSBC apparatus was mounted under the hood of a standard cone calorimeter [9], a Govmark CC-1. The cone heater was removed from the calorimeter. The cone calorimeter’s spark igniter was replaced by a hot wire igniter, which consisted of a coiled OMEGA NI80-010-200 resistance heating wire formed into a 22 mm diameter loop. This loop was suspended 5 mm above the top of an LIB specimen inserted into the CSBC apparatus. The igniter was powered by 56 W of AC electrical power, which produced a bright red glowing wire. The standard cone calorimeter igniter was not utilized in these experiments because it was found to be too small to provide simultaneous ignition of species ejected from all battery safety vent ports.

The rate of heat release associated with flaming combustion of the species ejected from the LIB during its failure, $P_{flaming}$, was measured as a function of time by quantifying the rate of consumption of oxygen in this well-ventilated, non-premixed combustion process and relating this consumption to the heat release through an empirical constant as defined by the standard [9]. Standard oxygen consumption calibration procedures were followed. The LIB failure was initiated using 20 W of continuous electric heating (the same power as was utilized in the stand-alone CSBC experiments). Five cone calorimetry tests were conducted for each battery type at each SOC to accumulate statistics. The $T_{slug}$ data, which were also obtained in these experiments, were not utilized for the internal heat generation calculations because the hot wire igniter contributed to the heating of the slug and its contribution was not easily quantifiable.

3. RESULTS AND ANALYSIS

3.1 CSBC Test Results

Representative copper slug temperature histories measured in the stand-alone CSBC experiments for all LIB types and SOC settings are shown in Figure 3. The onset of thermal runaway was detected by observing a sudden boost in the intensity of aerosol jets emanating from safety vent ports and concurrent sharp increase in $T_{slug}$. None of the LIBs at 0% SOC demonstrated an apparent thermal runaway.
Figure 3  Representative slug temperature histories recorded in CSBC experiments ($P_{in} = 20$ W).

With the exception of NMC cells at 100% SOC, the onset of safety venting temperatures were found to be in the range between about 450 and 470 K. The fully charged NMC cells started venting at temperatures 20 K below this range. The onset of thermal runaway occurred between 490 and 540 K in all batteries with the exception of fully charged LCO cells, for which the thermal runaway initiated 20 K below this range. Neither the safety venting nor thermal runaway temperatures demonstrated a clear trend with respect to SOC or battery chemistry. The heat capacity of the LIBs was evaluated and found to have no significant temperature or SOC dependence. Furthermore, within the uncertainties of the measurement, $c_{LIB}$ was found to be independent of the cathode chemistry and was not significantly affected by the battery failure events. The measured heat capacity value, 1.1±0.1 J g⁻¹ K⁻¹, is similar to those reported in earlier studies [16, 17].

Representative internal heat generation rates ($P_{IHG}$) computed by using Eq. (1) are shown in Figure 4. Even at 0% SOC, exothermic processes are detected in the LIBs. Two small exothermic peaks observed at low SOC for all battery chemistries (with the exception, perhaps, of the LFP cells) merge into a single, orders of magnitude taller peak as the battery SOC approaches 100%. The two peaks are speculated to be associated with the decomposition processes of the cathode and anode materials, which are triggered at somewhat different temperatures. In addition, each $P_{IHG}$ profile contains a small but persistent endothermic peak detected at all SOC and for all battery types. The timing of this peak corresponds to the onset of safety venting. This peak is speculated to be associated with the vaporization of electrolyte.
A numerical integration of the $P_{HG}$ curves was carried out and its results are presented in Figure 5. These integrals represent the total heat produced inside the battery between the onset of safety venting (including the endothermic peak) and the end of thermal runaway (or, in the case of 0% SOC, safety venting). The plot also shows the average internal heat generation rates computed by dividing the $P_{HG}$ integrals by the duration of time over which these integrals were taken. The total heats and average rates are plotted with respect to the electrical energy stored in the battery. It is important to note that unlike $P_{HG}$ integrals, average $P_{HG}$ values are specific to the thermal environment of the CSBC experiments and may differ significantly from the internal heat generation rates in other scenarios. These values are used here for comparative purposes.
Figure 5 Dependence of the total internal heat produced (left) and average internal heat generation rate (right) on stored electrical energy. The dashed lines are spline interpolations of the displayed experimental data points. The dotted line (in the left graph) is a hypothetical curve for an LIB if it produced heat equal to the stored electrical energy.

For all LIB types, both the total internal heat and the average rate of its production increase with increasing stored electrical energy. However, the rates of these increases become small or negligible as the battery SOC approaches 100%. The LCO released the most internal heat at the highest average rate followed by NMC and LFP cells. This order is consistent with the cell’s electric capacities. The LFP is the only battery for which the total internal heat falls below the stored electrical energy at 100% SOC (the dotted line in the left graph of Figure 5 represents a hypothetical battery for which the electrical energy and internal heat released are equal). The rest of the LIBs produce significantly more internal heat than the electrical energy that they contain.

3.2. Numerical Modeling Results

Through an inverse modeling exercise, the thermal conductivities of the LIBs were determined to be 1.0±0.1, 0.4±0.1 and 0.4±0.1 W m⁻¹ K⁻¹ for LCO, NMC and LFP cells, respectively. These thermal conductivities provide a good agreement (within 3%) between the measured and modelled copper slug and LIB axis temperature histories. While these cells were represented in the model as isotropic objects, the experimental design emphasizes radial conduction. Therefore, these conductivity values should be associated with radial direction.

The results of the experimentally derived \( P_{\text{HIC}} \) profile verification exercises for LCO cells are shown in Figures 6. The \( P_{\text{HIC}} \) profiles implemented in the simulations are shown next to the experimental data in the graphs on the left. A comparison of the \( T_{\text{slug}} \) computed using the \( P_{\text{HIC}} \) profiles as an input to the corresponding experimental data is shown in the graphs on the right. The simulated temperatures are within 5% of the experimental data, which indicates that the lumped heat capacity assumption invoked in the analysis of the CSBC experiments is generally valid.
Figure 6: Results of numerical modeling of the CSBC experiments performed for LCO cells. $P_{inc}$ is prescribed; $T_{slag}$ is simulated and compared with the experimental data.

### 3.3 Cone Calorimetry Results

Representative flaming combustion heat release rate ($P_{Flamg}$) histories obtained for all LIB types and SOC settings are shown in Figure 7. The curves are separated into 2 segments. One segment is associated with the safety venting, the other – with the thermal runway. With the exception of 0% SOC cells (which do not experience thermal runaway), the combustion energies released during these stages of failure appear to be similar in magnitude.
Figure 7  Heat release rate of flaming combustion of ejected LIB materials.

A numerical integration of the $P_{\text{flaming}}$ curves (including both safety venting and thermal runaway stages of failure) yields the total flaming heat of combustion. The $P_{\text{flaming}}$ integrals together with the average rates of heat generation, which were calculated by dividing the $P_{\text{flaming}}$ integrals by the corresponding failure durations, are graphically represented in Figure 8. As in the case of the internal heat generation, the total combustion heats and average rates are plotted with respect to the stored electrical energy.
The total combustion heats are between 0.3 and 70 times higher than the corresponding $P_{IHG}$ integrals. The rates of these distinct heat generation processes are even further apart, with flaming combustion being at least 3 times higher. Unlike $P_{IHG}$ integrals, $P_{Flaming}$ integrals do not demonstrate a systematic dependence on the cathode chemistry or SOC.

4. CONCLUSIONS

Copper Slug Battery Calorimetry (CSBC) was utilized to investigate the thermally-induced failure of 18650 lithium ion batteries containing three different cathode materials: lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP). Numerical simulations of transient heat transfer in these experiments were carried out to confirm the validity of the experimental findings. The heat capacity of all of the studied LIBs was determined to have the same value, 1.1±0.1 J g$^{-1}$ K$^{-1}$. The radial thermal conductivities of the LIBs were estimated to be 1.0±0.1, 0.4±0.1 and 0.4±0.1 W m$^{-1}$ K$^{-1}$ for LCO, NMC and LFP cells, respectively. The heat generated by the thermal failure processes inside the batteries was measured for a range of SOC settings and found to be the highest for LCO cells, about 37 kJ/cell at 100% SOC, and lowest for LFP cells, at about 14 kJ/cell at 100% SOC. This order of energetics was retained even after the internal heat was normalized by the stored electrical energy. In other words, while charged LFP LIBs did undergo safety venting and thermal runaway, they released the least amount of heat internally per unit electrical energy stored.

The CSBC technique was combined with cone calorimetry to measure the heat produced as a result of flaming combustion of the material ejected from the LIBs during failure. Fully charged LCO and LFP cells released comparable amount of combustion heat, about 50 kJ/cell. 100% SOC NMC cells released notably large amounts, around 65 kJ/cell.

ACKNOWLEDGEMENTS

The authors would like to thank the Ford University Research Program and Federal Aviation Administration, Grant #12-G-011, for supporting this research. We also would to thank the Federal Aviation Administration grant monitor, Dr. Richard E. Lyon, for constructive feedback.

REFERENCES


Full-Scale Fire Testing of Electric and Internal Combustion Engine Vehicles

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ABSTRACT

Fire exposure tests were conducted on electric vehicles (EVs) in comparison to analogous internal combustion engine vehicles (ICEVs). Plug-in hybrid electric vehicles (PHEVs) were also tested. Using the UL2580 standard as a guideline, each vehicle was exposed for 30 minutes to controlled conditions simulating a gasoline pool fire. The vehicle was kept in as realistic a condition as possible. Measurements of temperature, heat flux, heat release rate (HRR) and battery voltage were recorded. Overall, the EVs did not present a greater hazard than the ICEVs. The peak HRR and heat flux levels measured in the ICEV tests were due to the burning of a full tank of gasoline and were higher than those measured in the comparison EV tests. They also occurred earlier than or around the same time as in the EV tests. The response of the EVs to the fire appeared to depend on the vehicle model, battery design and state of charge. For one model, the primary peak in HRR resulted from burning of the non-battery vehicle components, while a subsequent secondary peak, associated with high heat flux levels, occurred once the battery pack was fully compromised. For the other model, burning of the battery pack did not contribute to any significant increases in HRR or heat flux above the levels generated by the other vehicle components. The results from the PHEVs were consistent with those from the EVs and ICEVs.

KEYWORDS: electric vehicle, plug-in hybrid electric vehicle, internal combustion engine vehicle, battery pack, full-scale fire test

INTRODUCTION

As the numbers of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) on public roads increase, more information is needed to determine the relative fire safety of these vehicles and the large battery packs powering their propulsion system. In an abuse situation, the energy in the battery packs may be liberated, leading to potential safety hazards. Some fire testing has been conducted on EV batteries alone (e.g. [1, 2]), without the influence of other vehicle components, while other experiments have simulated fires in full-scale EVs and PHEVs. A number of these have focused on the scenario of a self-sustaining fire, in which a small burner was used to ignite part of the vehicle (typically not the battery) and remained lit only until the fire could be sustained by the vehicle’s own components [3-5]. One study exposed an EV to a small (30 kW) propane fire for 11 min, sufficient to induce thermal runaway and generate a self-sustaining fire in the battery pack [6]. A few other studies have involved a larger propane or gasoline burner under the vehicle to generate a partially engulfing fire, but either the battery pack was removed for safety reasons [7] or a mock-up of an EV was used [8]. Thus, there remains a need to examine in detail the scenario of a large external fire engulfing a real EV.

In the present work, a series of full-scale fire tests were conducted to compare EVs, PHEVs and conventional internal combustion engine vehicles (ICEVs) under exposure to external fire conditions simulating a fuel spill fire. The results of this work will assist in evaluation of the relative safety of EVs, PHEVs and their battery packs under fire exposure. It will also help guide the development of technical regulations for these vehicles.
EXPERIMENTAL SETUP

All fire tests were conducted inside the burn hall of the National Research Council Canada full-scale fire test facility in Carleton Place, Ontario, Canada. The test area was situated under a 6 m by 6 m exhaust hood connected to an exhaust fan system, which was used to collect the smoke and hot gases produced by the fire. A 2.4 m by 1.2 m propane sand burner was used to generate the fire exposure to the vehicle. The flow of propane was distributed over the entire burner surface using a network of steel piping covered by a bed of 9.5 mm diameter rocks that were spread across the area of the burner. Flame temperatures measured in the 2 MW propane fire were around 800°C, similar to those measured in a gasoline pool fire of the same area. Thus the burner provided a repeatable, controllable fire source that could simulate a gasoline pool fire.

A mounting platform was built around the burner, with the top of the platform level with the rim of the burner. The test vehicle sat directly on the platform, centred over the burner, so that the top of the platform acted as the ground plane underneath the vehicle (Figure 1). For all tests, the car was supported on cinder blocks to prevent it from dropping to the ground as the tires burst in the heat of the fire. Thus the ground clearance was maintained constant at 203 mm, the height of the cinder blocks. For each vehicle, all windows and doors were fully closed. All tires, shocks, fuel lines, air bags, etc. remained in place, without modification, to allow as realistic a simulation as possible. Prior to ignition of the propane burner, the car’s electronics systems were energized, although the engine remained turned off.

A total of 7 full-scale fire tests, each of 30 minute duration, were conducted on 3 EVs, 2 PHEVs and 2 ICEVs (Table 1). For Vehicle A, the ICEV was not identical to the EV, but was of similar size (the ICEV was slightly smaller) and from the same manufacturer. For Vehicle B, the ICEV and EV were of the same model, with different propulsion systems. The EV models of Vehicles A and B contained similar battery energy storage capacities, but Vehicle B contained two separate battery packs in different locations instead of a single pack, as in Vehicle A. Vehicles C and D were PHEVs from different manufacturers, with Vehicle C having a smaller battery than Vehicle D. As indicated in Table 1, the gas tank was filled completely and the battery pack was charged to either 100% or 85% (as indicated by the driver readout) prior to testing.

![Figure 1](image1.jpg) **Figure 1** Typical experimental setup, shown with preliminary test vehicle. Note that the preliminary vehicle was not supported on cinder blocks, unlike in all other tests.
Table 1  Test vehicles.

<table>
<thead>
<tr>
<th>Generic vehicle designation</th>
<th>Specific vehicle designation</th>
<th>Vehicle type</th>
<th>Model year</th>
<th>Gas tank</th>
<th>Battery capacity</th>
<th>State of charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A-ICEV</td>
<td>ICEV</td>
<td>2015</td>
<td>full</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>A</td>
<td>A-EV-100</td>
<td>EV</td>
<td>2014</td>
<td>--</td>
<td>large</td>
<td>100%</td>
</tr>
<tr>
<td>A</td>
<td>A-EV-85</td>
<td>EV</td>
<td>2013</td>
<td>--</td>
<td>large</td>
<td>85%</td>
</tr>
<tr>
<td>B</td>
<td>B-ICEV</td>
<td>ICEV</td>
<td>2013</td>
<td>full</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>B-EV</td>
<td>EV</td>
<td>2013</td>
<td>--</td>
<td>large</td>
<td>100%</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>PHEV</td>
<td>2013</td>
<td>full</td>
<td>small</td>
<td>85%</td>
</tr>
<tr>
<td>D</td>
<td>D</td>
<td>PHEV</td>
<td>2014</td>
<td>full</td>
<td>medium</td>
<td>100%</td>
</tr>
</tbody>
</table>

Instrumentation

All temperature measurements were made using Type K, 24-gauge, bare-bead thermocouples. In accordance with UL 2580 [9], six of these thermocouples were evenly spaced inside a 2 m long, stainless steel tube centred approximately 25 mm below the vehicle’s underside and aligned with the vehicle’s longitudinal midplane. Two additional tubes, each also containing six thermocouples, were placed on either side of the first tube, separated by a centreline-to-centreline distance of 0.33 m.

A thermocouple tree, consisting of 5 thermocouples spaced 0.25 m apart, was located inside the vehicle near the centre of the passenger cabin, with the highest thermocouple approximately 0.1 m below the ceiling. Additional thermocouples were attached to the metal floor of the vehicle (on the internal surface of the chassis), to the underside of the vehicle (external to the passenger cabin), in the engine compartment, and on the exterior and interior of the battery pack. Voltage measurements were obtained from the high voltage battery pack (at the main high voltage relays) and the 12 V accessory battery. For Vehicle C only, additional voltage measurements were obtained from selected individual battery cells (at the cell terminals).

Two Gardon gauges [10] were used to measure radiative heat flux from the burning vehicle. One gauge faced the rear of the vehicle at a distance of 3.9 m from the burner centre (although its view of the entire vehicle rear was partially blocked by an existing wall in the test area), while the other faced the passenger side of the vehicle at a distance of 3.1 m from the burner centre. Both gauges were positioned 1.2 m above the top of the burner, near the mid-height of the car windows.

Smoke and gases produced by the fire were collected using the exhaust hood system located above the vehicle. Heat release rate (HRR) was determined using oxygen consumption calorimetry [11], with correction for CO₂ and CO. Gas samples were also taken from inside the passenger cabin, at head height near the driver’s seat (approximately 0.25 m below the ceiling), and sent to either an FTIR spectrometer/continuous gas analyser to measure concentrations of major species (including CO₂, CO, HCN, HF and HCl), or a smoke meter to measure smoke optical density.

All instrumentation cables and sampling lines from inside the vehicle were routed out of the vehicle through an opening that would not significantly affect conditions inside the vehicle. This was typically a hole in the roof with filler around the wires. In a few tests, thermocouples from the battery pack were routed through an additional hole in the rear passenger-side door. Data sampling for all instrumentation except those on the battery pack occurred at a rate of 0.2 Hz for two tests (A-ICEV and C) and 0.5 Hz for all other tests. For the battery instrumentation, sampling occurred at between 0.5 and 1 Hz for temperature and between 1 and 10 Hz for voltage, depending on the test. Video cameras at different viewing points were used to record the fire during testing. The weight of each vehicle was also measured before and after testing.

The results presented in the next section focus on the external hazards posed by the vehicle and do not include data from all of the instrumentation described above.
RESULTS

Vehicle A

Figure 2 shows the average temperature-time curves from the thermocouples in the stainless steel tubes underneath Vehicles A-ICEV, A-EV-100 and A-EV-85. Overall, the temperature underneath the vehicles was approximately 800°C, although there was some variation (+150/-100°C) due to differences between tests. For instance, the underside of both EVs had a plastic cover (approximately 2 mm thick) over the battery, which likely burned within the first 5 minutes of the test, resulting in higher temperatures being reached underneath the EVs during that period than for the ICEV. This was supported by the HRR data, shown in Figure 3, which were higher during the first 5 minutes for the EVs than for the ICEV.

Each of the EVs also experienced a sudden increase in temperature underneath the vehicle midway through the test, around 10 min for A-EV-100 and 14 min for A-EV-85 (Figure 2), which corresponded to a simultaneous increase in HRR. (For A-EV-100, the HRR data channel was lost just after 10 min, but a subsequent increase in HRR similar to that seen for A-EV-85 was expected). These peaks in HRR and temperature coincided with sudden spikes in radiative heat flux from the vehicle, as shown in Figures 4 and 5, as well as with long, intense flames being emitted from underneath the vehicle, indicating that they were related to burning of the battery pack.
Figure 6 Voltages and selected temperatures from A-EV-85 battery.

As seen in Figure 6, the voltage measurements from the battery pack for A-EV-85 showed an initial decrease at approximately 7 min, followed by a second decrease at 10 min and a final decrease to 0 V at 13 min. The voltage drops likely corresponded to individual battery modules being compromised. The voltage drops at 7 and 13 min were each accompanied by a sudden spike in temperature at one of the thermocouple locations inside the battery pack. The decrease at 7 min was also accompanied by a series of visible sparks and flashes emitted from the battery pack. The decrease to 0 V at 13 min occurred just before the peak in HRR at 14 min, indicating that the pack was fully compromised and becoming fully involved in the fire. Indeed, beginning at 15 min, the thermocouples in the battery pack underwent a final temperature increase that eventually exceeded 800°C by 25 min.

For Vehicle A-EV-100, the data channels from the battery pack failed about 5 min into the test, so very little battery temperature and voltage data were available. However, it is apparent that between 5 and 10 min, the HRR and heat flux from the passenger side of A-EV-100 were similar in magnitude to those of A-ICEV (Figures 3 and 5). Note that these two vehicles were reasonably similar in size and were expected to have similar amounts of combustible materials, except in the propulsion system. The similarities in HRR and heat flux levels therefore suggest that the non-battery components of A-EV-100 provided the primary contribution to the overall HRR and heat flux between 5 and 10 min. The contribution of the gas tank contents of Vehicle A-ICEV may be seen at about 6 min, corresponding to a sudden spike in the HRR and heat flux (Figures 3-5). This spike was of very short duration, suggesting that the gasoline was released all at once. In comparison, the battery in A-EV-100 likely did not become fully involved in the fire until later, at around 10 min, when significant spikes in temperature (Figure 2) and heat flux (Figures 4 and 5) were observed. That the battery involvement occurred earlier for A-EV-100 than for A-EV-85 may have been due to the higher state of charge of the A-EV-100 battery.

Vehicle B

Figure 7 shows the average temperature-time curves from the thermocouples in the stainless steel tubes underneath Vehicles B-ICEV and B-EV. Overall, the temperatures remained around 800°C, although there was some fluctuation (+50/-100°C) and variation between tests. The decrease in temperature underneath Vehicle B-ICEV at around 7 min corresponded to large increases in HRR and radiative heat flux, as shown in Figures 8-10. This was likely caused by release of the gas tank contents, which would have created a fuel-rich environment immediately underneath the vehicle, resulting in lower temperatures there, but increased temperatures and heat flux further out around the vehicle where there was enough air for the fuel vapours to burn.
Figure 7  Average temperatures under Vehicle B.

Figure 8  HRRs for Vehicle B (including 2 MW burner contribution).

Figure 9  Radiation from rear of Vehicle B.

Figure 10  Radiation from passenger side of Vehicle B.

Figure 11  Voltages and selected temperatures from B-EV rear battery.

Figure 12  Voltages and selected temperatures from B-EV front battery.
Figures 11 and 12 contain voltage and selected temperature data from the two battery packs in Vehicle B-EV. Based on Figure 11, the rear battery high voltage system became compromised just after 11 min, when the voltage measurements dropped to 0 V. This was accompanied by sudden spikes and dips in the measurements from the thermocouples in the front battery pack (Figure 12), suggesting electrical interference with those data channels. Although the validity of the temperature data from both battery packs is questionable after 11 min, their rapid increase starting around 13 min suggests that both packs were at least partially compromised by this time. At 16 min, the voltage measurements from the front battery pack decreased to 0 V (Figure 12), indicating compromise of the front battery high voltage system.

The times when the voltage readings dropped to zero provide only some indication as to when the battery packs themselves were compromised, since the voltage measurements were made at the main pack relays (which could have failed separately) and not at the battery cell level. As indicated earlier, the thermocouple measurements inside the battery pack were also suspect after 11 min due to potential electrical and/or chemical interference from the compromised high voltage systems. The video recordings, however, provided visible and audible evidence of battery pack compromise, with a series of popping sounds and flashes underneath the vehicle at 12 min and another series of pops, flashes and flares near the passenger-side rear wheel well just before 20 min.

It should be noted that the two B-EV battery packs did not have the same configuration. The rear pack contained two modules of different size, with the larger module located on top of the smaller one. Meanwhile, the front pack contained two modules of the same size located at the same elevation in the vehicle. Thus, the responses of the two packs to the fire underneath the vehicle would be expected to differ. The front pack was directly exposed to the fire and its compromise may have corresponded to the flashes underneath the vehicle at 12 min. On the other hand, the larger module of the rear pack was initially shielded by other vehicle components (including the smaller module below it) and may have been compromised around the time of the flashes near the rear wheel well at 20 min.

Examining Figures 7-10, there are no distinct increases in temperature, HRR or heat flux at either 12 or 20 min. In fact, between 10 and 30 min, the HRR and heat flux data from Vehicle B-EV were comparable to those from B-ICEV. Differences between the two vehicles prior to 10 min were mainly due to the contribution by the gasoline in B-ICEV to higher HRR and heat flux levels. For B-EV, the HRR peaked at 10 min, while peak heat flux levels occurred at or before 10 min. Most likely, these were primarily due to burning of the non-battery vehicle components, since they occurred before any indication of battery pack compromise. Therefore, this particular battery did not seem to contribute to any significant increases in HRR or heat flux above the levels generated by the other vehicle components. This may have been due to the battery chemistry, its construction and/or its thermal management system.

**Vehicles C and D**

The average temperature-time curves from the thermocouples in the stainless steel tubes underneath Vehicles C and D are shown in Figure 13. For reasons unknown at this time, the temperatures under Vehicle C decreased gradually over the course of the test from above 800°C to 600°C. However, for Vehicle D, the temperatures remained approximately constant at 800°C throughout the test.

Figures 14-16 show the HRR and heat flux data for Vehicles C and D. For Vehicle C, the highest levels of HRR occurred between 6 and 10 min, with a secondary peak occurring around 15 min. The heat flux measurements were in agreement, with Figure 16 showing the same trends as Figure 14, and Figure 15 showing several spikes in the data between 5 and 8 min. Based on Figure 17, which contains plots of battery temperatures and cell voltages, the battery started to become involved in the fire at approximately 5 min, when sharp spikes in the interior temperature measurements suggest electrical interference with the thermocouple channels. Measured voltages from the individual battery cells decreased to 0 V during the period between 6 and 9 min, indicating that those cells were compromised. Pack voltage measurements were unsuccessful in this test.
Figure 13  Average temperatures under Vehicles C and D.

Figure 14  HRRs for Vehicles C and D (including 2 MW burner).

Figure 15  Radiation from rear of Vehicles C and D.

Figure 16  Radiation from passenger side of Vehicles C and D.

Figure 17  Selected temperatures and cell voltages from Vehicle C battery.

Figure 18  Voltages and selected temperatures from Vehicle D battery.
From the video recordings, a series of popping sounds and visible sparks were emitted from the battery pack between 13 and 16 min, followed by another series of bright flashes and flares between 19 and 27 min. The first series occurred at the same time as the secondary peak in HRR and heat flux at 15 min (Figures 14 and 16), indicating burning of the battery components. The second series did not correspond to any significant increase in HRR, although there was a slight increase in heat flux from the rear of the vehicle (Figure 15), which likely would have been more distinct had the heat flux gauge been able to view the entire rear of the vehicle.

The above data suggest that for Vehicle C, the battery pack was compromised and started to burn by approximately 6 min, contributing to high levels of HRR between 6 and 10 min. Other vehicle components would have also contributed to these high levels, including, most likely, the gas tank contents. As the test progressed and the battery components became more fully involved in the fire, they contributed, at around 15 min, to a smaller, secondary increase in HRR above the levels generated by the other vehicle components. Starting at 19 min, the burning battery produced a series of bright flashes and flares, but these did not appear to release significant amounts of heat.

Turning now to Vehicle D, Figure 14 shows two large spikes in HRR between 7 and 9 min, corresponding to a simultaneous increase in heat flux from the passenger side of the vehicle (Figure 16) and to very large, intense flames emitted from the rear of the vehicle. These flames were observed to extend past the edge of the exhaust hood above the test area, so the HRR values plotted between 7 and 9 min are likely underestimates of the actual magnitudes. The flames also damaged the heat flux gauge facing the rear of the vehicle, resulting in loss of data just after 7 min in Figure 15. This event was most likely caused by release of the gas tank contents; it should be noted that Vehicle D was the only one with a metal gas tank. After the gasoline burned off, the HRR and heat flux remained relatively constant until shortly after 10 min (11 min for heat flux in Figure 16, 13 min for HRR), when they started to decrease gradually until the end of the test.

Based on Figure 18, which shows voltage and selected temperature data from the battery pack, the voltage measurements at the main pack relays decreased to 0 V at 6 min, indicating compromise of the high voltage system. The voltage drop was accompanied by spikes and dips in the thermocouple measurements, with further spikes and dips occurring a few minutes later, between 8 and 9 min. By 15 min, when most of the thermocouple measurements became erratic, the battery was likely fully involved in the fire.

The above data suggest that for Vehicle D, burning of the battery and other vehicle components (beyond the gas tank) contributed to the relatively higher levels of HRR and heat flux measured between 9 and 13 min, compared to the remainder of the test. It is currently unclear as to what was the source of the small spike in HRR and heat flux at 19 min (Figures 14 and 16), although it may be battery-related. For this particular vehicle, the contents of the metal gas tank appear to be the greatest hazard, while the battery pack did not seem to cause any large spikes in either HRR or heat flux.

Peak HRR, Total Heat Release and Effective Heat of Combustion

Based on the results presented above, Table 2 lists, for each vehicle, the peak HRR, its time of occurrence, the total heat released during the fire and an effective heat of combustion estimated using the measured mass loss. The heat release data in Table 2 do not include the contribution by the 2 MW burner. From the first two columns, it is apparent that the peak HRRs for the ICEV models were greater than those for their EV counterparts. Also, the times of peak HRR for the ICEVs were similar to or earlier than those for the EVs. Given that the peak HRR for the ICEVs corresponded to burning of the gas tank contents, the above trends suggest that a vehicle with a full gas tank produces a greater hazard in terms of HRR than one with a battery pack.
Table 2  Heat release data for each vehicle, without 2 MW burner contribution.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Peak HRR (MW)</th>
<th>Time of peak HRR (min)</th>
<th>Total heat release (MJ)</th>
<th>Mass loss (kg)</th>
<th>Mass loss (%)</th>
<th>Effective heat of combustion (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-ICEV</td>
<td>7.1</td>
<td>6.0</td>
<td>3290</td>
<td>274</td>
<td>25%</td>
<td>12</td>
</tr>
<tr>
<td>A-EV-100</td>
<td>6.0</td>
<td>7.0</td>
<td>--</td>
<td>333</td>
<td>23%</td>
<td>--</td>
</tr>
<tr>
<td>A-EV-85</td>
<td>5.9</td>
<td>5.8</td>
<td>4910</td>
<td>295</td>
<td>20%</td>
<td>17</td>
</tr>
<tr>
<td>B-ICEV</td>
<td>10.8</td>
<td>8.0</td>
<td>4950</td>
<td>336</td>
<td>25%</td>
<td>15</td>
</tr>
<tr>
<td>B-EV</td>
<td>6.9</td>
<td>10.2</td>
<td>4660</td>
<td>363</td>
<td>22%</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>6.0</td>
<td>7.5</td>
<td>4630</td>
<td>308</td>
<td>21%</td>
<td>15</td>
</tr>
<tr>
<td>D</td>
<td>7.9\textsuperscript{a}</td>
<td>8.3</td>
<td>5850\textsuperscript{a}</td>
<td>445</td>
<td>26%</td>
<td>13</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Actual value likely higher.

The data in Table 2 for total heat release and effective heat of combustion do not show a clear pattern between ICEs and EVs. For Vehicle A, the total heat release of A-ICEV was 33% lower than that of A-EV-85 (part of this may have been due to A-ICEV being slightly smaller), while for Vehicle B, the total heat release of B-ICEV was 6% higher than that of B-EV. With the vehicle mass loss being approximately the same between each EV/ICEV pair, the effective heats of combustion exhibited similar trends as the total heat release.

Two earlier works have compared heat release data from analogous ICEVs and EVs. Similar to the present study, Lecocq [3] found the peak HRR to be higher for the two ICEVs tested than for the two corresponding EVs. Unlike Table 2, however, the total heat release and effective heats of combustion were also higher for the ICEVs. Meanwhile, Watanabe [4] found the peak HRR and total heat release to be higher for their EV, but in that study, the ICEV was noticeably smaller than the EV (more so than for Vehicle A).

The peak HRRs in Table 2 are somewhat higher than those measured in the above studies. Lecocq [3] reported a peak HRR of 6.1 MW for one ICEV, compared to peak values between 4.2 and 4.8 MW for the other ICEV and two EVs. Watanabe [4] reported peak HRRs of 6.3 MW for the EV and 2 MW for the smaller ICEV. One possible reason for the higher peak HRRs in Table 2 is the presence of the 2 MW burner underneath the vehicle in the present tests, whereas the fires of Lecocq [3] and Watanabe [4] were both self-sustained by the vehicle’s own components. Nevertheless, peak HRRs of up to 10 MW have been previously reported for ICEVs [12-14], so overall, the HRR data in Table 2 are consistent with the literature. The values for total heat release in Table 2 also fall within the range of those found in the literature, from 2000 to 10000 MJ [3, 4, 12-15]. (It should be noted that the data from Lecocq [3] (6300-10000 MJ) are expected to be on the high end of this range because they contain a correction for soot production [16].)

The mass loss percentages in Table 2 are slightly higher than the published values, which generally range from 15 to 20% [3, 4, 15, 17]. This is likely because the post-test measurements in the present experiments were made using a crane scale and did not include the mass of anything that fell or was projected off the vehicle during the test. Assuming that the mass of this residue was about 5% of the post-test measurement, the mass loss percentages would instead be 16-22%, in better agreement with those in the literature. The effective heats of combustion would then be approximately 20% higher than those listed in Table 2 (14-21 MJ/kg) and closer to the 22 MJ/kg value that was determined by Mangs [15] and used by several researchers [4, 17] to estimate heat release from their mass loss measurements. Nonetheless, it may be noted that effective heats of combustion as low as 10 MJ/kg have been reported for passenger vehicles [14].
CONCLUSIONS

For the vehicles tested under the fire conditions examined in this study, the presence of a battery-powered propulsion system did not present a greater overall hazard than the conventional gasoline-based propulsion system. For the ICEVs tested, the release and burning of the gas tank contents caused spikes in HRR and heat flux above the levels produced by the other vehicle components and corresponded directly to the peak values. These peak values were typically higher than those measured for the corresponding EVs. They also occurred earlier than or around the same time as for the EVs.

In the EV tests, the response of the battery pack to the fire depended on the vehicle model, i.e. on the battery design, location and construction. The tested EVs of Vehicle A exhibited two peaks in HRR, with the first, primary peak likely caused by burning of the non-battery vehicle components and the second, smaller peak caused by burning of the battery pack once it was fully compromised. Peak heat flux levels coincided with the secondary peak in HRR. The state of charge appeared to affect the timing of the secondary peak, with a higher state of charge corresponding to an earlier secondary peak. In comparison, burning of the battery pack in Vehicle B-EV did not contribute to any significant increases in HRR or heat flux above the levels generated by the other vehicle components. Although consistent trends between the EV and ICEV models were observed in the HRR data from both Vehicles A and B, there was no discernible pattern between the EVs and ICEVs when examining the total heat release or effective heats of combustion.

The data from the PHEVs were consistent with those from the EVs and ICEVs. For Vehicle C, the peak HRR and heat flux levels occurred during the early stages of battery pack burning, so the battery pack likely contributed only partially to those high levels. The gas tank contents and other vehicle components outside the propulsion system would have also made significant contributions. Similar to the EV model of Vehicle A, a secondary, smaller peak in HRR was observed midway through the test, corresponding to the battery pack becoming fully involved in the fire. For Vehicle D, the metal gas tank was the greatest hazard, with significant spikes in HRR and heat flux associated with the release and burning of its contents. In comparison, burning of the battery pack did not seem to cause any large spikes in either HRR or heat flux above the levels generated by the other vehicle components, similar to Vehicle B-EV.

The values for peak HRR, total heat release and effective heat of combustion in Table 2 compare reasonably well with those found in the literature, although there is a large range of published values. Differences in experimental conditions and in methods for determining the heat release data would need to be further examined in order to improve comparison between the present results and those previously published.

REFERENCES


Investigation of a LPG Tank Rupture During a Car Fire

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ABSTRACT

Cars do only explode in movies. A fact taught in the firefighters training around the world. Thus, an incident in August 2014 made the experts sit up and take notice. A Ford Focus equipped with a retrofit LPG system crashed against a tree in northern Germany and caught fire. During firefighting, the LPG tank ruptured, leaving 10 firefighters injured. The rupture ejected the tank throwing it over a distance of about 35 meters. The follow up investigation of the retrofitted vehicle showed the correct installation and maintenance history of the LPG system in accordance to the European and German regulations. The plugging of the pressure release device (PRD) led to the increase of pressure due to the exposure to the fire and finally to the rupture. The paper describes the technical investigation of the vehicle and its LPG components.

KEYWORDS: lpg, fire investigation, tank rupture, pressure release device, post collision vehicle fire, alternative fuel, explosion, car fire fighting

INTRODUCTION

In August 2014, a car crashed against a tree frontally. Resulting from the impact a fire started in the engine compartment, spreading to the whole vehicle within the next minutes. When the fire brigade started to extinguish the burning car the LPG tank retrofitted in the spare wheel well ruptured. Ten firefighters were injured, five of them severely.

The incident led to a broad and most often little substantiated discussion with in many cases preposterous demands. Especially in the first days, when the causes were still unknown, the call for labelling all cars running on alternative fuels was loud. In addition, the gas related part of the periodical technical vehicle inspection (ptvi) mandatory in Germany and the legal framework for retrofit solutions were put into question.

The body of public prosecutors and the police commissioned DEKRA to do the accident reconstruction, the fire investigation, and to investigate the causes of the tank rupture.

BASIC STATISTICS

On January 1, 2016, the vehicle licensing statistics of the German Federal Motor Transport Authority (Kraftfahrt-Bundesamt KBA) counted 54,602,441 vehicles. 45,071,209 of them were passenger cars. Gasoline is still the most common fuel, followed by Diesel. Just about 1.6% of the registered passenger cars are running on alternative fuels or alternative propulsion concepts. Figure 1 shows the share of the different fuels. Figure 2 shows the development of the registration figures of passenger cars in Germany running on alternative fuel or having an alternative propulsion system. [1][2]
Figure 1  Share of passenger car fuels and propulsion concepts in Germany on January 1, 2016 [1]

Figure 2  Development of the numbers of passenger cars using alternative fuels or alternative propulsion concepts in Germany [2]

About 6,250 LPG filling stations were available in Germany in 2012. About 30,000 stations cover Europe. [3] No information is available about the number of fire incidents with LPG or CNG fuelled cars.

ON-SCENE ACCIDENT INVESTIGATION

The accident investigator responded to the scene immediately after commissioning. On arrival, all evidence relevant objects still were at their original positions. The investigator and the Police together carried out the acquisition of accident data.

The accident occurred on a straight rural road in northern Germany. The speed limit was 100km/h. It was a sunny morning in August; the paved road surface was dry. The burnt out vehicle stood on the right side of the road (seen in its former driving direction) at a tree. Partially scrape off marks at the tree bark of the tree’s trunk showed the impact location. The embankment had a fall of 22°. The car rotated counter clockwise by 25°. Figure 3 shows the final rest position of the car.
Tire marks on the shoulder and the state of the car indicate that the driver has not shown any signs of reaction when leaving the road for several seconds.

The car’s retrofitted LPG tank lay in a distance of 37.5m on the neighboring field. It was torn open on one side, Figure 5.
VEHICLE INFORMATION

The car was a European model of the Ford Focus. The first registration of the five-door hatchback dated to August 2005. In 2008, the conversion of the car to a bi-fuel system by retrofitting an Autogas (Liquefied Petroleum GAS/LPG) system took place. This was done by a garage specialized on gas conversions. All required documents were on hand. The day before the incident, the car had its bi-annual ptvi at a DEKRA location. Here the odometer displayed about 128,000 kilometers. The inspection engineer identified several severe faults at the car’s chassis. All of them were irrelevant for the accident occurrence. The inspection of the LPG-system was part of the ptvi, too. No faults were identified here.

The gas system consisted of the following main-components:

- Toroidial internal tank mounted in the spare wheel well. The tank, manufactured by Stako, had a volume of 53l.
- BRC internal multivalve including all the mandatory components like pressure relief valve (PRV), 80% automatic filling stop/automatic cut-off, solenoid valve at the outlet, excess flow valve, non-return valve, manual (service) valve and mechanical level indicator. The valve was not equipped with an optional thermo-fuse element (PRD).
- BRC engine kit with e.g. ECU controller, reducer, LPG injectors rail, gas level sender, and vapor gas filter.

All components were type approved for the European market. The system setup accorded to the European and German legal requirements. All required components were built-in. All gas lines were copper tubes. The tubes were clamped to the chassis, not to other hoses or lines. This indicates a high quality conversion.

ACCIDENT RECONSTRUCTION

The deformations at the vehicle’s front allowed an unambiguous assignment of the impact position against the tree. The straight on track of the rolling wheels on the embankment and missing marks on the pavement indicated that there was no loss of control over the vehicle before the impact. There has neither been any reaction of the driver. The reconstruction of the collision speed led to 75km/h to 85 km/h.

FIRE INVESTIGATION

Due to the severe consequences of the incident, the body of public prosecutors wanted to know more about the fire’s cause. The investigator used the process of elimination (as also described in NFPA standard 921 [4]) to narrow down the cause of fire. At this point, follows the description of the relevant steps only.
The vehicle was severely deformed on the left side of the front. The impact against the tree led to deep intrusions in the area around the left head light. Due to the impact, the left wheel housing and the longitudinal chassis beam contacted the bulkhead.

The impact destroyed the battery, located on the left side of the engine compartment. Nevertheless, after removing the fire debris, the battery’s lead plates and the connecting wiring could be uncovered. The wiring did not show any signs of a short circuit. The grounding connection to the chassis was in good condition. Also all other wiring found in the vehicle did not show any hints for a short circuit. It can be assumed that the destruction of the battery and the alternator shut down all electric power within the seconds of the collision. An electric ignition is thus very unlikely.

The burn pattern indicated a more severe fire load on the left side of the engine compartment. Removing the fire debris in this sector, the area between the gear and the firewall became visible. Several wires and brake lines were pinched. The wires did not show any marks of a short circuit. The brake lines were connecting the brake force booster with the rear brakes. The lines were torn open. The backward displacement of the engine led to a contact of parts of the exhaust system with the damaged brake lines. At that type of car, the brake fluid reservoir is attached on top of the brake’s main cylinder. The screwing connecting the brake’s main cylinder with the brake force booster was uncovered. Parts of the main cylinder’s housing were still detectable here. The fire has consumed the rest of the cylinder.

According to the location of the brake fluid reservoir and the damage pattern, the impact destroyed or disconnected the reservoir. The leaking brake fluid than dropped on the hot exhaust manifold. With a flashpoint below 100°C and an inflammation point below 300°C brake fluid can easily ignite at the exhaust manifold.

The further investigation showed a broken gear case. The ignition point of gear oil is a little above 200°C. The leaking gear oil got direct contact to hot parts of the exhaust system.

The lines of the gas system were running on the right side of the engine compartment. The relevant parts of it were undamaged due to the collision. All screw connections were still in place.

The fire started due to the contact of combustible fluids, released by the crash’s deformations, with the hot surface of the exhaust system.

INVESTIGATION OF THE EXPLOSION

The first step was the examination of those gas system’s components that remained in the vehicle. Mounted to the right front wheel housing was a solenoid valve. This was still in very good condition. The attached copper lines were properly connected. As mentioned in the vehicle information chapter, all lines were made of copper. The remains indicate a very professional and good quality laying and attaching of the lines.

The rupture of the toroidial tank destroyed the rear end of the car, Figure 6. On both sides – the tank and the chassis - were remains of the connecting lines. No other parts of the gas system were found at the first examination. The next step was the analysis of the debris. The aluminum parts of the vaporizer found in the debris were molten. Thus, a detailed analysis of possible leakages, breakages, or a faulty installation became impossible. The nearly undamaged gas-filter and the injector rail were also found in the debris. Nothing pointed to a causal defect here.
The investigation and analysis of the gas system’s part in the vehicle did not point to a faulty installation or a pre-crash defect leading to the crash, the fire or the rupture. An in-depth examination of the vaporizer was not possible due to the degree of damage. Its original location outside the vehicle’s deformed area argues against the vaporizer as the ignition source.

The examination of the toroidal tank and the associated components was step three. The tank showed the typical damage symptoms of an overpressure rupture. About one third of the tank’s outer body was ripped out. The breaking edge was bent outward. The torn out piece looked like rolled up. The separated top cover of the tank was also blast away. All components had been exposed to the fire. Figure 7

Figure 8 shows the multivalve. That remained in the center of the tank. The inspection proved its appropriate installation.
The multivalve consisted of the following relevant components:

- filling connector with a non-return valve
- solenoid valve at the outlet to the engine line
- excess flow valve
- 80% automatic filling stop/automatic cut-off
- mechanical level indicator
- pressure relief valve (PRV)

All connections between multivalve and tank were installed correctly. The plastic parts of the valve located outside the physical gas filled part of the tank were molten or burnt away. When dismounted, the rubber seal between tank and valve became visible. This was undamaged. Clamped to the valve’s PRV connector was a piece of a natural rubber house was, Figure 9. The tank rupture had destroyed the components of the level indicator.
The examination of the multivalve led to an interesting issue at the PRV. Apparently, it was moving freely. After removing the correctly clamped piece of hose and a protective cap, a view inside the valve became possible. Small rubber parts were conspicuous here. The further dismounting of the valve brought out a larger rubber part jammed inside the valve. The follow up dissection showed, that the rubber part filled out the connector completely. Big efforts were required to remove the rubber part. The dismounting is documented in Figure 10 to Figure 12.

Figure 10  View inside the PRV from the outlet-side
The extracted rubber part was a part of the rubber hose connected to the PRV. The originally function was to reach in the gaseous phase of the gas tank. Thus, in case of a PRV activation, only the gaseous and not the liquid phase is released. A microscopic analysis of the hose showed porousness at the outer area. So far, there was no follow up analysis whether the hose was porous because of a fault in the material, the usage of inappropriate material or the heat.

RESULT

The analysis and reconstruction leads to the following course of events:

The car crashed against the tree with a minimum speed of 75km/h to 85km/h. There was no reaction of the driver to avoid the collision. The impact lead to severe deformations of the car, primarily on the left front. Displacements of the engine, the gearbox and the other components mounted in the engine compartment led to jamming of brake lines and the destruction of components containing combustible liquids. Those were set free and got in direct contact with parts of the hot exhaust system. The fire started here and spread to the whole car.

The toroidial tank of the retrofit LPG system was exposed to the fire. That led to an increase of pressure inside the tank. The witness reports of the at scene fire fighters state a whistling sound directly before the explosion. That supports the assumption that the PRV started to work correctly. The stream of the escaping gas transported parts of the rubber hose – loosened by an unknown reason – into the valve’s connector. Here it got stuck and closed the outlet. The gas could no longer escape, leading to a further increase of pressure inside the tank. Exceeding the bursting pressure at a mark of about 35bar, the tank burst.
CONCLUSIONS FOR FIRE FIGHTING

Ten injured fire fighters – an incident that requires an investigation of what went wrong to learn for the future. One aspect was that the fire fighters did not know that the car was equipped with a LPG system. Though such cars do usually not explode during a fire, the activation of the PRV leads to a loud noise and a large flame. Thus, the call for a special marking of alternative driven vehicles became loud. The problem of that approach is of course, that the fire destroys such markings in a very early stage. More promising is the inquiry of the vehicle data stored at the KBA via the license plate number. That system is already popular in the Netherlands and is becoming more popular in Germany now. Besides information about the type of car and its used fuel(s) the dispatch center can directly send the suitable rescue sheet with the relevant vehicle information.

The two fire fighters at the nozzle stayed uninjured thanks to their protective turn out gear. The other fire fighters wore their gears and helmets too, but their faced were not protected. The breathing apparatus’ masks were not required a few meters away from the burning car. Two fire fighters did not wear their protective gloves for using the radio. Distance and coverage pose the best safety measurement here – a limited option for fire fighters. Nevertheless, all fire fighters not directly required in the first line should stay away from the burning vehicle as far as possible. That is true for all kinds of vehicles, independent of the propulsion system and fuels used. Fire engines should be parked outside a safety radius of at least 15 meters.

The helmet saved one fire fighter’s life. A vehicle part thrown away by the explosion hit his helmet leaving that severely damaged. The fire fighter stayed nearly uninjured.

The usage of the complete personal protective equipment is essential for all rescue personnel during the vehicle firefighting. All fire fighters not involved in the direct firefighting should use the coverage of the fire engine. Marshaling areas are to be well spaced out.

The quality of the site investigation by the officer in charge decides about the success of the mission. This is also true for scenes of an – on the first view - minor incident.

REFERENCE LIST

Design Fires for Railway and Metro Tunnels

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ABSTRACT

Design fire scenarios represent a major input to conduct fire safety engineering assessment of compliance to performance-based regulations. This work aims to derive idealized design fire curves for railway and metro tunnels based on a review of existing data.

KEYWORDS: review, fire safety, experimental fire tests, railway transportation, design fires.

INTRODUCTION

Over the last two decades, more than 30 major fires occur in rail or metro/LRT tunnel worldwide, emphasizing the need of constant improvement of fire safety measures. The large majority of these 30 major fires took place in a metro or LRT tunnel. Half of them were caused by a technical failure onboard of the train and the other half by arsons or external fire sources.

Fire sources origins categorize in (1) electrical failure mainly cables fires related to power trip (2) mechanical failure e.g. hot axle box or locked axle brake and (3) accidental ignition or arson in passenger cars. Passenger trains and metro or LRT trains do not face the same risk level regarding fire. Metro high service frequency, operation and passengers occupation rates increase the risk of a fire by both technical failure and arsons. Long distance trains and particularly high-speed trains however can develop similar risk levels.

Since the 1980s, regulators and operators have been discussing prevention measures for passenger rolling stocks at national level. French standards NF F 16-101, NF F 16-102 and NF F 16-103 specify a comprehensive framework to fire performance requirements for materials and products to be used on rolling stock. Standardisation efforts across Europe lead to publication of the European standard EN 45545 [1]. The standard intend to protect passengers and staff in railway vehicles in the event of a fire on board. Its 7 parts detail the measures and requirements depending on hazard levels established considering operation and design categories. New rolling stock both in railway and metro applications, while complying with all the requirements of the standard, limit the spread of a fire on board and minimise fire consequences (heat, smoke and toxic gases namely) on passengers. Existing rolling stock tend to perform in similar way. Operators modernize their rolling stock fleet on regular refurbishment programs.

Since the early 2000s and the catastrophic fires in Mont-Blanc, Tauern and Gotthard tunnels, fire consequences in a tunnel environment have been a major concerns for regulators and tunnel operators. As part of the on-going railway interoperability policy in the European Union (EU), a technical specification of interoperability (TSI) has been issued since 2008 for safety measures in European Network railway tunnels. A revised version enlarging the scope to railway tunnels above 100m in length of the rail system of the entire EU has been enforced since 1st January 2015 [2].

The SRT (Safety in Railway Tunnels) TSI defines a coherent set of tunnel specific measures for the infrastructure, rolling stock and operation subsystems to reach an optimal level of safety in tunnels. The general principle of the SRT TSI comprises four successive layers to tackle risks in tunnels:
prevention, mitigation, evacuation and rescue. The TSI relies on performance-based standards such as EN 45545 to provide safety measures for tunnel-specific railway incident.

For hot incidents (e.g. fire, explosion followed by fire, emission of toxic smoke or gases) the TSI lists the appropriate mitigation measures and the expected objectives. However, the TSI does not provide approved and shared design fire scenarios required to assess passengers’ evacuation conditions or to design active smoke control systems.

To derive idealized design fire curves for rail and metro rolling stock this work reviews operators current practices, theoretical approaches to estimate the heat release rate of various materials involved in a complete passenger car and experimental data from small and full-scale fire tests.

THEORETICAL APPROACHES

Building a design fire curve for a given rolling stock can be quite straightforward. The simplest theoretical approach only needs the total fuel load in MJ and an estimated burn duration to define an average heat release rate (HRR). NFPA 130 [3], back in 1983, provided guidance for the burn duration and topped it to 30 minutes.

For any given rolling stock, the total fuel load is calculated from individual fuel loads considering for each material the mass involved and its heat of combustion. As an example, let us consider a locomotive fire. Figure 1 represents parts of a typical high-speed train locomotive.

![Figure 1 Scheme of a typical high-speed train locomotive (top view). Green square represents the cables area and the red pattern outlines the main converter.](image)

Total energy potential can be estimated to 76 GJ where oil from the main converter represents up to 43% and cables in the locomotive 23%. Using the method from NFPA 130, this locomotive can produce a 42 MW fire as a complete burn in 30 minutes. Obviously, this method leads to quite over-estimate HRR as it assumes complete burn down of the considered rolling stock, was it a passenger car or a locomotive.

Duggan proposed in [4] an alternative method to better predict the HRR in case of fire spread to an entire carriage interior. Based on cone calorimeter experiments, he derived a heat release rate per unit area for each burning materials. The specific HRR produced by each burning material is given by multiplying the exposed surface to fire of this material and the HRR per unit area obtained by a cone
calorimeter test. For the entire carriage, total HRR is estimated by summation of individual materials HRR.

Duggan claimed his method to be superior to the total fuel load calculation as it takes into account individual material contribution to the total HRR based on location and exposed face to the fire. The cone calorimeter database at the heart of the method defines three irradiance levels depending on the location of the material:

- 50 kW/m² for horizontal prone (ceiling)
- 35 kW/m² for vertical
- 25 kW/m² for horizontal supine (floor)

Keeping our previous example from Figure 1, the Duggan method is used to provide a time-dependent HRR evolution. Considering an oil leak from the main converter of 100 l/min, Figure 2 provides an estimate of the total HRR.

![Figure 2](image)

**Figure 2**  
HRR time evolution for a locomotive fire considering a 100 l/min leak in the main converter.

A HRR peak can be observed up to 45 MW. On a 30 min duration, the average HRR can be calculated to roughly 40 MW. This value is close to the one obtained with the previous method.

The implicit assumptions the Duggan method is based on, as outlined by White in [5], do not make it a useful improvement of the total fuel load calculation. Summation of cone calorimeter data for combustion of single material samples cannot represent fire spread and complex interactions between materials that react to fire on different manners.

Both methods also neglect the physical and dynamic behaviour of a fire as outlined on Figure 3. From ignition, a fire exhibits a growth phase followed by a fully developed burning activity and then a decay phase.
Fire growth rate are usually referred to considering the time to reach 1 MW. NFPA 92B [6] and Quintiere [7] categorize 4 fire growth rates based on t-squared HRR curves (see Figure 4):

- Ultrafast (1 MW reached in 75 s)
- Fast (1 MW reached in 150 s)
- Medium (1 MW reached in 300 s)
- Slow (1 MW reached in 600 s)

When considering a fire source inside a passenger train carriage, a large bin fire grows in the range of a slow to medium rate whereas a gas burner can be considered as a slow fire growth rate. Fast and ultrafast fire growth rate are more typical of liquid hydrocarbon fires like in locomotive converters.

In dealing with fire development in a tunnel environment, tunnel ventilation can have a significant impact on fire growth even if the fire is enclosed inside a carriage. Casalé et al. [9] showed that, depending on fire source configuration and longitudinal airflow inside the tunnel, the HRR expected
from the fire can be increase by a factor 1.7 to 2 at worse. Other studies for freight lorry shuttles
introduced a HRR corrective factor $A\sqrt{H}$, depending on the area $A$ and the height $H$ of the opening.

Table 1 sums up publicly available design fires scenarios available for rail or metro systems. Values
are mainly obtained by total fuel load calculations and can account for tunnel ventilation impact.
Sparse data are available and tunnel operators perform risk analysis and refer to a design fire scenario
representing the HRR of their current rolling stock on a case-by-case basis.

<table>
<thead>
<tr>
<th>Average HRR</th>
<th>Project name/reference</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive fires</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 to 30 MW</td>
<td>Oresund Tunnel [9]</td>
<td>1994</td>
</tr>
<tr>
<td>Passenger car fires</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 to 14 MW</td>
<td>New York City Transit [13]</td>
<td>2011</td>
</tr>
<tr>
<td>10 to 40 MW</td>
<td>Gotthard Tunnel [14]</td>
<td>2012</td>
</tr>
</tbody>
</table>

Depending on tunnel configuration, ignition source, materials involved, there are significant
discrepancies between the data. Values do not only depend on the type of rolling stock but also on the
type of system in the tunnel to be design. For instance, in the Gotthard Tunnel [14], a 10 MW HRR
was specified for design of the ventilation/smoke extraction system, whereas passive protection was
designed considering a 40 MW fire.

Statistical approaches based on events trees [15] allow tunnel operators to lower the HRR of a typical
fire scenario. However, assumptions made during the process require validation at all stages.
Experimental data are required to better understand the fire spread and improve the theoretical
approaches described previously.

**REVIEW OF EXPERIMENTAL DATA**

Quite a few real scale data are publicly available due to tunnel fire tests high costs. In the context of
railway tunnels, three main fire tests programs are reviewed: EUREKA 499-project [16], Carleton
University fire tests [17] and METRO project [18]. Experimental ventilation conditions, ignition
sources, tested rolling stock represent key variables to discuss the results of these tests and to derive
idealized design fire curves.

**EUREKA 499-project**

During the EUREKA project (1990 to 1992), three real scale tunnel fire tests involving railway rolling
stock took place. A metro car in aluminium, an IC train car and an ICE train car were tested in a
tunnel facility in Norway. Longitudinal airflow was set at 0.5 m/s and 6.2 kg of isopropyl alcohol
were used for ignition. Figure 5 shows the HRR obtained for the all three cars tested.
The three different cars have various heat potential: the metro car represents 41 GJ, the ICE train car 63 GJ and the IC train car 77GJ. These values explain in part the fire development observed on Figure 5. For the metro car, the aluminium roof melted quite early during the test resulting in an airflow increase inside the carriage and a fast fire growth rate. The resulting HRR peak is estimated to 35 MW. For the two train cars, the HRR average values are close to each other, falling in the range 10 to 12 MW. However, the ICE train car exhibits a delayed HRR peak after 70-80 minutes burning.

**Carleton University fire tests**

Fire tests of a metro and a train car were conducted at the Carleton University (Canada) tunnel mock-up facility. It intends to represent 37.5 m long, 10m wide and 5.5m high real tunnel [17]. The tunnel mock-up offers a transverse ventilation system to measure accurately the HRR.

Figures 6a and 6b represent the HRR measured for the metro car and the train car inside the facility. Ignition source was a gas burner, which delivers the EN 45545 [1] recommended HRR, e.g. 75 kW for the first 2 min and 150 kW for 8 min. Air velocity was set at 2.4 m/s.
For the train car, only one lateral slide door was opened. 5 min after ignition, two windows broke allowing fresh air to get inside the car and to spread the fire. Finally, the fire reached its maximum HRR value (32 MW) after 18 minutes when all the windows broke.

For the metro car, despite the lower heat potential, fire spread tends to be quicker than for the train car. In this test, all 4 lateral sliding doors were opened leading to a fast fire growth and a peak HRR of 52.5 MW.

These two tests highlight how ventilation conditions inside the tunnel (longitudinal airflow) and inside the carriage dramatically impact fire spread and fire HRR. As for the EUREKA fire tests, metro cars develop higher HRR but on a shorter time period.

**METRO project**

The Swedish research project METRO (2009-2012) aimed at assessing hot incident (fire, explosion, …) risks in a metro network [18]. Part of the work was to define realistic design fires based on small-scale experiments, CFD simulations and real scale tunnel fire tests. The project significantly focused on passengers’ luggage impact on the fire HRR. An individual additional HRR of 100 kW was estimated for a single piece of luggage.

Two tunnel fire tests were conducted based on a X1 metro car from Stockholm metro operator. Each car has an heat potential estimated to 35.4 GJ. 4 kg of luggage were also distributed evenly inside each car leading to an additional heat potential of 7.2 GJ. Figure 7 represents the HRR evolution for these tests.
Figure 7  

HRR evolution for the METRO tunnel fire tests [18].

Similar behaviour is observed for the two fire tests. However, the second one (named Test 3 on Figure 7) is significantly delayed in time with a peak HRR reached 118 minutes after ignition. The second X1 metro car was refurbished with HL3 (Hazard Level) class lining material according to the EN 45545 standard [1].

METRO project recommends considering as design fire HRR values for metro systems:
- 60 MW with a fast fire growth rate in case of an arson
- 20 MW with a medium fire growth rate in case of a metro car with materials according to the latest fire reaction standards stopped in station.
- 20 MW with a medium fire growth rate for a metro car stopped in tunnel with closed doors.

Recent small-scale tests.

In addition to the small-scale tests performed in METRO and previously described, laboratory scale tests have been conducted in the TRANSFEU project [15] to assess spreading from the EN 45545 ignition source [1] to materials in a passenger rolling stock. These tests performed on seats and wall lining highlighted the increase in material fire reaction with the current standard. Materials add limited HRR to the ignition source (in the range 100 to 200 kW) and prevent fire spread.

However, upscaling to a complete car is still an issue as fire spreading is highly sensitive to test conditions. Location of the ignition source is also a sensitive variable in fire development. In the TRANSFEU fire tests, the ignition source is placed in front of the seat whereas in Carleton University fire tests, the ignition source is located behind the seat, resulting in different fire development and HRR.

DISCUSSION

Experimental data for railway tunnel fires are quite sparse and present significant discrepancies depending on the rolling stock age (e.g. old, refurbished to equivalent fire reaction standards or new), ignition source (e.g. EN 45545 gas burner, liquid fuel), tunnel ventilation conditions, type of rolling stock (e.g. rail or metro/LRT cars), additional heat potential from luggage. This starting point makes almost impossible to derive and propose idealize design fire curves for fire-life safety issues.

METRO fire tests and TRANSFEU experiments tend to prove the benefits of stringent fire reaction standards. Fire can be largely delayed (METRO) or significantly reduced by preventing fire spread.
(TRANSFEU). During its operation lifetime, a passenger rolling stock undergoes 3 to 4 refurbishment cycles. Typical fire behaviour of old rolling stock, as highlighted in EUREKA 499 or Carleton University fire tests with an average HRR around 15 MW during 30 min, has a lower and lower probability.

To derive idealized design fire curves for fire-life safety issues, the method used is similar to the one discussed in [19]. For fire-life safety issues, peak HRR is not relevant of toxic compounds and temperature production from the fire. For users safety, fire growth rate and average HRR are key variables to assess evacuation time and conditions.

Design of ventilation systems also does not required peak HRR value. The system might be overwhelmed during the peak but it remains crucial that it can cope with the smoke produces by the fire during the global evacuation time and fire-fighting operations. Therefore, linear fire growth rate based on a medium t-squared curve are used and the HRR is considered constant for a time period equivalent to the global energy released by the fire. Examples of proposed idealized design fire curves are highlighted on Figure 8 based on experimental data reviewed previously.

![Graph](image)

(a) Old Metro/LRT car

![Graph](image)

(b) Refurbished Rail car

**Figure 8** Examples of proposed idealized design fire curves (solid line) based on experimental data (dashed lines)
As outlined in METRO project, impact of passengers’ luggage can be significant on the HRR. Being out of standards materials, luggage can spread quickly the fire and contribute to a large extent to the HRR. Kaprun funicular fire in Austria in 2000 was an infamous instance of this phenomenon.

Theoretical insights on fire spread and materials fire behaviour are required to predict fire behaviour inside a railway tunnel. Numerical models and trusted theoretical approaches can improve the knowledge database of fires in such environment. Expanding TRANSFEU work to different fire source location and different configurations can be a way to derive more general design fire curves for new rolling stock.

REFERENCES

Design Fires in Swedish Railway Tunnels – How are Research Results Implemented and What are We Missing?

Niclas Åhnberg, Axel Jönsson, Brandskyddslaget, Sweden

ABSTRACT
This paper addresses the process of deriving design fires for Swedish railway tunnels. The paper describes a method for this process, developed by Brandskyddslaget and amended by the Swedish Transport Administration. The focus of the paper is on two subjects; the first is to describe the method and the second is to describe how present research results are implemented in the process. Current knowledge gaps, where further research is needed, is also highlighted in order to facilitate further development of data for a research based approach to design fires in railway tunnels.

KEYWORDS: Railway tunnels, design fire, heat release rate.

INTRODUCTION
In Sweden, evacuation analyses in tunnels are used for two purposes; one is to investigate the contribution to the overall risk of travelling in the tunnel (expressed as an F/N-curve) and the other is to conclude whether self-evacuation is possible in the majority of all large fire-scenarios for the tunnel. In these analyses, many other factors such as occupant load, air velocity in the tunnel and the position of the train are treated as variables [1]. Although the fire development in a tunnel can be expected to vary, the design fire has historically been treated as a discrete variable.

In the last 15 years, approximately the same design fire has been applied for evacuation analysis in Swedish railway tunnel projects. A review of Swedish railway tunnel projects show that the design fire has almost exclusively been a fire growth rate equivalent to the NFPA medium curve (0.012 kW/s²) with a peak heat release rate (HRR) of 15 MW [2]. These assumptions have been based on the results in the EUREKA fire tests [3].

The EUREKA fire tests were conducted in the beginning of the 1990’s and much has happened in terms of performed research on the subject and development of computational tools in fire safety [4]. Also, there can be significant differences between the trains in the tunnels and the trains that have been used in the fire tests such as fire barriers, layout and burning behaviour of materials like internal claddings and seats. Naturally, this affects the conditions under which a design fire should be chosen for evacuation analyses.

This paper addresses the process of deriving design fires for Swedish railway tunnels. The paper will describe a method developed by Brandskyddslaget and amended by the Swedish Transport Administration [5]. By creating representative design fires that are more customized to the project-specific conditions, the tunnel safety systems can be optimised in regards to a functional and economical perspective. The paper will focus on two subjects; the first is to describe the method and the second is to describe how present research results are implemented in the process. Current gaps in knowledge, where further research is needed, will also be highlighted in order to facilitate further development of data for a research based approach to design fires in railway tunnels.
METHOD DESCRIPTION
To determine the risk contribution from fires in a tunnel it is important to know what kind of fire scenarios that are possible in the specific tunnel. It is also important to know how large portion of all fire scenarios that can be represented by a certain heat release rate curve. In order to treat the heat release rate as a probabilistic continuous variable when performing a fire safety analysis, a new method for determining design fires has been developed. It is limited to heat release rate curves used for evacuation analyses and discussions regarding the conditions for the rescue services.

The result from using the method is not one single design fire but a range of representative design fires for different possible fire scenarios in the tunnel are developed. The method consists of the following steps:

*Step 1 - Go through the different possible train types that will be used in the tunnel and describe their fire characteristics.*

Although a variety of trains can be used and there are uncertainties regarding the future, the most common types of trains are to be selected, and their share of the conducted traffic estimated. The selected train types should be investigated regarding materials (primarily shell, insulation, seats, linings on walls, ceilings, and floors), which fire safety standards that are fulfilled, compartmentation, fire barriers, number of floors, windows and doors.

In Sweden, the tunnel safety analysis is conducted for the predicted traffic about 20 years after opening. More common than not, the project traffic forecasts includes an estimate on which types of trains that are meant to be used in the tunnel. Especially in Metro-projects where the owner of the system can choose strict requirements on the trains, the tunnels or a combination in order to achieve an acceptable level of risk in the system.

*Step 2 – Set fire scenarios for all types of trains*

The following fire scenarios could be used unless other scenarios are deemed to be more appropriate:

A. Fire with small ignition sources (electrical faults, small pieces of luggage and play with fire)
B. Fire in a passenger compartment starting in a vandalized seat or an ignition source larger than an average pile of newspaper and smaller than an average piece of luggage (10kW - 200kW)
C. Fire in a passenger compartment starting with an ignition source larger than an average piece of luggage (>200kW)
D. Significant fire in the undercarriage (including further fire spread)
E. Significant fire in the drivers cab (including further fire spread)
F. Fire in locomotive

10 kW is selected as it corresponds to the paper cushion used as ignition source in seat testing according to the German standard DIN 5510 and European norm EN 45545. 200 kW covers most pieces of luggage that were investigated during the METRO-project [6] and testing has shown that fire spread along walls requires several hundred kW for most modern panels.

These scenarios can be altered or divided into further subcategories that are more relevant for the train type in question. It can for example make a great difference in which part of the passenger area that the fire starts.

Step 3 – Set probabilities connected to each fire scenario
In this step, the portion of the overall fire events in the tunnel that can be associated to each fire scenario is to be set. Based on statistics gathered by the Swedish Transport Administration and the Swedish Civil Contingencies Agency the following probabilities can be used for Swedish passenger trains without locomotives:

Scenario A (small ignition sources): 85 %
Scenario B (vandalized seat or medium sized piece of luggage): 2.5 %
Scenario C (large ignition source): 2.5 %
Scenario D (undercarriage): 9 %
Scenario E (drivers cab): 1 %

This is also to be divided with each train type that traffics the tunnel. Table 1 shows how this could look.

<table>
<thead>
<tr>
<th>Ignition source</th>
<th>Train type 1</th>
<th>Train type 2</th>
<th>Train type ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Scenario 1-A (Share %)</td>
<td>Scenario 2-A (Share %)</td>
<td>Scenario ...-A (Share %)</td>
</tr>
<tr>
<td>B</td>
<td>Scenario 1-B (Share %)</td>
<td>Scenario 2-B (Share %)</td>
<td>Scenario ...-B (Share %)</td>
</tr>
<tr>
<td>...</td>
<td>Scenario 1-... (Share %)</td>
<td>Scenario 2-... (Share %)</td>
<td>Scenario ...-... (Share %)</td>
</tr>
</tbody>
</table>

Step 4 – Derive representative heat release rate curves for each fire scenario
Further on, deriving representative heat release rate curves can be done in 3 levels of detail; (1) rough estimate, (2) fire development analysis or (3) fire development analysis combined with supplementary fire testing.

Rough estimate
Rough (conservative) estimates can be used based on the fire characteristics that were derived in step 1. In [5] the following heat release rate curves are suggested and motivated.
### Table 2. Examples of heat release rate curves based on rough estimates [5]. Growth rates (Slow, Medium & Fast) are according to NFPA 92 Appendix B.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Ceiling and walls: Incombustible</th>
<th>Other materials: BS 6853 Vehicle Category 1 or EN 45545-2 HL 2</th>
<th>Materials: BS 6853 Vehicle Category 1 or EN 45545-2 HL 2</th>
<th>Worse materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>The passenger compartment is not ventilated through open exterior doors. (Exterior doors are not opened in the fire affected car, exterior doors are self-closing or interior doors prevents ventilation through the lobbies)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Small ignition sources</td>
<td>Slow 1 MW</td>
<td>Slow 1 MW</td>
<td>Medium 1 MW</td>
<td></td>
</tr>
<tr>
<td>B. Vandalised seat or medium sized piece of luggage</td>
<td>Slow 10 MW</td>
<td>Slow 1 MW and continuing acc. to Medium 15 MW</td>
<td>Medium 20 MW</td>
<td></td>
</tr>
<tr>
<td>C. Large ignition source</td>
<td>Medium 2 MW and continuing acc. to Slow 15 MW</td>
<td>Medium 20 MW</td>
<td>Fast 1 MW and continuing acc. to Medium 25 MW</td>
<td></td>
</tr>
<tr>
<td>D &amp; E. Undercarriage or Drivers cab</td>
<td>Slow 10 MW</td>
<td>Slow 2 MW and continuing acc to Medium 15 MW</td>
<td>Slow 2 MW and continuing acc. to Medium 20 MW</td>
<td></td>
</tr>
<tr>
<td><strong>The passenger compartment is ventilated through open exterior doors.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Small ignition sources</td>
<td>Slow 1 MW</td>
<td>Slow 1 MW</td>
<td>Medium 1 MW</td>
<td></td>
</tr>
<tr>
<td>B. Vandalised seat or medium sized piece of luggage</td>
<td>Slow 15 MW</td>
<td>Medium 20 MW</td>
<td>Medium 20 MW</td>
<td></td>
</tr>
<tr>
<td>C. Large ignition source</td>
<td>Medium 15 MW</td>
<td>Fast 20 MW</td>
<td>Fast 60 MW</td>
<td></td>
</tr>
<tr>
<td>D &amp; E. Undercarriage or Drivers cab</td>
<td>Slow 15 MW</td>
<td>Slow 2 MW and continuing acc. to Medium 20 MW</td>
<td>Slow 2 MW and continuing acc. to Fast 60 MW</td>
<td></td>
</tr>
</tbody>
</table>

**Fire development analysis**
When using fire development analysis, the time to ignition and a heat release rate curve is estimated for individual zones of the train. The HRR-curves for each zone are then added into a total HRR-curve for the car. Studies of conducted experiments supplemented with temperature, radiation and smoke/temperature calculations (e.g. CFD-calculations) can be used to estimate the ignition time. Crucial assumptions are: ventilation openings at different stages of the fire (door openings and breaking windows), HRR and fire load of exposed combustible surfaces, fire spread rate and fire barriers.
This kind of analysis has been performed in at least three Swedish tunnel projects including the extension of the Stockholm Metro.

The HRR of initial phase of the fire depends on the ignition source, adjacent materials such as seats, luggage, walls, and ceilings and whether the fire starts in a smaller compartment or in a large compartment. The initial phase of the fire is studied by adding HRR-curves for individual items and surfaces until the fire size is large enough to create a local flashover and consequently more rapid fire spread along the car.

**Example: Stockholm Metro [16]**

The cars that are meant to operate in the extension of Stockholm Metro are called C20 and C30. They have mainly incombustible linings and insulation in the walls and ceilings with seats that fulfill the EN 45545 standard.

The HRR-curve for small ignition sources (A) is not deemed to be more severe than a slow growing fire with a peak of less than 1MW. This assumption is based on the high level of fire protection and the fact that EN 45545-5 tests vandalized seats for ignition sources up to 10kW.

Medium scale testing in the METRO-project (mockup of one third of a car) shows that a fire size of 2-3 MW is required to create a local flashover and fire spread along a large passenger compartment when the fire is located in a corner of a car with incombustible linings (0.7-0.9 MW with combustible linings) [15]. This was later confirmed in the full scale testing where the fire had a HRR of 3MW before fire spread along the passenger compartment occurred [7]. The small scale experiments showed that fire spread between seating groups required pieces of luggage placed between the seats or fire spreads via combustible linings and a flashover [15].

When adding the HRR-curves of a four-seat group, the average luggage according to the METRO-project and the flooring it can be concluded that the fire size does not exceed 1 MW and that the majority of fire load in the seats are consumed before fire spread is likely to adjacent seating groups. Medium size ignition sources in the passenger compartment (B) are therefore not likely to create a more severe fire than a medium fire growth (0.012 kW/s²) up to a peak HRR of 2 MW.

The only place where the walls are combustible is in the gangway. Based on the fire classification of the material in the bellows and test results for a baby-trolley in the METRO-project it is deemed unlikely that the HRR would exceed 2 MW in the C20 (see figure 2 below) or 1 MW in C30 where the bellow is reached the highest fire rating according to EN 45545-2. As there is no end-wall close to the gangway in C20 it is unlikely that rapid fire spread will occur in any of the cars even if the ignition source is larger than 200kW (scenario C).

![Figure 2. Resulting (“Totalt”) HRR-curve for a rubber bellow (“Bälg”), baby trolley (“Barnvagn”) and flooring (“Golv”) in a C20 car.](image)
However in an extreme scenario, including arson or an unfortunate amount and placement of luggage, the fire could spread along the car. The METRO-project showed that even in these conditions the fire spread to other seating groups could take a very long time (40 min in the full scale experiment) [7] but the time to fire spread was significantly reduced in the analysis of C20 and C30 with regards to the possibility of more luggage between the seats than in the full scale experiment.

The HRR-curve of the following phase with a more rapid fire spread along the car has been estimated by adding HRR-curves for different zones (segments) of the car. In all studied full scale experiments the fire travels along the car, which is mimicked in this approach. The time until ignition of the next zone depends on the spread rate along the car (m/min). A higher spread rate and a higher fire load means that a larger portion of the vehicle will burn simultaneously before the fire load is consumed at the fire origin.

When comparing full scale experiments it is clear that the fire spread and increase of HRR is much more rapid when the exterior doors are open in each end of the passenger compartment [3,7,8,9]. The temperature and radiation from the fire has to be break windows along the car in order to obtain oxygen in the unburned areas of the car if ventilation via external doors is limited. Ventilation can be limited if the exterior doors are not opened in the fire affected car, exterior doors are self-closing or interior doors prevents ventilation through the lobbies. This phenomenon was very noticeable in the Eureka tests of intercity cars [3].

![Figure 3. Comparison between full scale experiments with intercity trains with limited ventilation (to the left) and subway/commuter trains with well-ventilated fires through external doors [2,7,8 & 9]. The Korean IC-train did have open external doors in the vestibules in each end of the train although they were not as large as the Korean subway car.](image)

The same is noted in small scale experiments [10, 11]. Small scale testing in the METRO-project also reveals that there is great difference in fire spread rate along the car between combustible and incombustible linings. With incombustible linings on the walls and ceilings in a car with open doors the spread rate decreased from about 1.6 m/min (which corresponded well to the full scale experiments [7]) to about 0.45m/min in the small scale testing [11].

Using a fire spread of 0.5 m/min and HRR-curves for the different zones the following total HRR-curve was derived for C20:
The sensitivity analysis included spread rate along the train and HRR per unit area for surfaces with uncertain values. Spread rate along the train had the greatest impact and the resulting HRR-curve for this extreme scenario was approximated with a curve which was slightly less severe than a NFPA Medium fire with a peak HRR of 15 MW fire for a C20 vehicle. The same procedure was conducted for the C30 vehicle. The C30-vehicle has significantly lower fire load in the flooring and smoke screen doors between compartments resulting in a significantly lower HRR-curve.
CFD-modelling was conducted of a fire including the fire load inside a C20-vehicle. The purpose was to validate if the ceiling temperatures would indicate a more rapid fire spread than that of the METRO-experiments.

C30 has an aluminum structure and casing. It has been argued that aluminum carriages have a potential for more rapid fire growth rate and a higher peak heat release rate than steel carriages since the roof can melt and add ventilation [10]. The Eureka project involved a test of an aluminum subway car and a test with one half of a steel car and one half of an aluminum car. The subway car had open windows and an open door in the direction to which the fire spread [18]. The result was supplementary ventilation for a rapid fire growth during the initial 5 minutes after which the HRR peaked at 35 MW in the experiment. The materials in C30 are deemed to have better fire performance than the subway car in the experiment and the fire load is very low in C30.

In the test the fire was ignited in the aluminum half of the car, the fire was under ventilated and had a HRR of 2 MW for 40 minutes. At that time the fire spread to the steel car, with older materials, and back to the aluminum car at the same time as a hole was created in the aluminum roof resulting in an extremely rapid fire growth. The aluminum in the structure has no impact on the initial phase of the fire before local flashover. In C30, the aluminum structure and the underlying insulation could be proven to have a certain fire rating. The ventilation through the open exterior doors and the fact that the fire is assumed to start travel along the car long before the aluminum structure can be expected to melt reduces the effect on the spread rate along the car.

The total HRR-curves for fires starting in the undercarriage (D) and in the driver’s cab (E) were studied separately and derived in the same manner as the fire starting in the passenger compartment.

The initial phase of a fire starting in the undercarriage of the car (D) was based on the report from a real cable fire starting in the undercarriage in an older train in the Stockholm Metro with fire spread in...
to the passenger compartment holes created by electrical arcing through the floor. The fire was estimated to have had a slow-growing fire spread up to between 2 and 4 MW after 20 minutes [12]. The closed external doors had led to self-extinction inside the car. The C20 and C30 are equipped with technical measures preventing the accident from repeating, cables with better fire rating and with a stronger fire barrier in the floor. The scenario in C20 and C30 included a slow growing fire up to 2 MW which spread to the passenger compartment via open doors.

Figure 6. Estimated HRR in a real fire event in the Stockholm Metro [12].

Example: Double decker vehicles in Strängnästunneln [17]
Double decker vehicles can result in rapid fire spread and high peak HRR. The Swedish tunnel project Strängnästunneln included an analysis of a double decker vehicle with high standards on the seats, walls and mainly incombustible ceilings. The analysis was conducted in the same manner as in the metro extension project. For the double decker CFD-calculation and research on the impact of compartment geometry from earlier projects were used to determine the time to local flashover in the smaller compartments and fire spread between the compartments.

Figure 7. CFD-modelling for determining time to ignition of different floors/zones of a double decker car. Fire starting in one of the mezzanine compartment.

Figure 8. Summation of HRR-curves for different compartments in a double decker car.
Fire development analysis combined with supplementary fire testing
This is basically the same analysis as above, but in order to minimize uncertainties, supplementary
fire testing is conducted. This is more expensive but gives, of course, the most reliable results. There
are several German projects where full scale tests were conducted within the scope of the project
[4,13]. Another example is the Swedish project Citytunneln in Malmö which included small scale
testing of individual seats in three of their trains in order to determine the fire spread in the initial
phase with an ignition source slightly larger than 10kW. The seats were tested in complete seating
groups and with a cone calorimeter in order to calculate time to fire spread between seating groups
[14].

Step 5 – Place the heat release rate curves in order of their severity
The HRR-curves that correspond to the scenarios identified in step 2 are here to be ranked in order of
their severity, i.e. their effect on evacuation. One HRR-curve can represent more than one scenario.
For each curve, the probabilities are cumulated, see table 3.

Table 3. Examples of summatting the HRR-curves.

<table>
<thead>
<tr>
<th>HRR-Curve (start with least severe case)</th>
<th>Share (the sum of all scenarios which the curve represents)</th>
<th>Cumulative share</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve no 1 (description)</td>
<td>A %</td>
<td>A %</td>
</tr>
<tr>
<td>Curve no 2 (description)</td>
<td>B %</td>
<td>A+B %</td>
</tr>
<tr>
<td>Curve no ...</td>
<td>... %</td>
<td>A+B+... %</td>
</tr>
<tr>
<td>Curve no ...</td>
<td>F %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

Finally, the cumulative share that each HRR-curve covers is calculated (see column 3 above). The
most severe HRR-curve will cover all evacuation scenarios, i.e. have a cumulative share of 100 %.

Step 6 – Select design fire curves
How many HRR-curves that are used in the further scenario analyses of evacuation safety depends on
how detailed the further analyses needs to be. It is recommended that the curves are treated as a
variable in most cases (at least two HRR-curves should be chosen and studied further). The selected
curves should represent possible outcomes. It should be stated how large portion of the possible fires
that the chosen curves represents.

Uncertainties
As with all analysis, there are uncertainties regarding many factors such as potential fire growth,
probability of each ignition source and the future traffic, etc. If applied correctly, the method uses
worst probable case fire development for each scenario, and hence the method generates a
conservative result for most tunnel projects.

AREAS WHERE FURTHER PUBLICLY AVAILABLE RESEARCH IS OF INTEREST
In order to further develop the use and precision of this method both small, medium and full scale
testing is of interest. One flaw that has been identified in some performed experiments is that the
publicly available documentation of the experiments is not always comprehensive enough to have as a
basis for valid judgements. Supplementary description of the spread rate along the car, the fire
characteristics of the individual materials and components and small scale sensitivity analyses would
often help. The METRO experiments [6,7,11,15] are examples of how experiments could be
documented in order to be as useful for practitioners as possible.

There is also a lack of performed tests with incombustible linings in the roof (with incombustible
insulation and normal amounts of cables above) but combustible linings in the walls. The effect of this
kind of setup would be useful to see as it is not uncommon. Other areas of interest where
supplementary testing would be helpful are; cars that are built according to the worst possible combination of materials that would pass different standards or norms such as EN 45545; sleeping cars; double decker cars; locomotives and freight wagons.

CONCLUSIONS
The presented method has been applied in several Swedish tunnel projects during the last couple of years. The usage of the method has, in these projects, been regarded as a successful way of overviewing different scenarios and their probabilities. When performing fire safety evaluation of tunnels it is deemed more justifying to use a method based on the current research status and traffic in tunnels rather than selecting design fires based on single, or few, experimental data points which was the previous state of the art.

Even though the described method is developed with respect to Swedish railway tunnels it is considered to be a generally applicable tool that can be used when preforming a fire safety analysis for a railway tunnel, regardless of country and legislation.

REFERENCES
5. Dimensionerande brandefekt i persontåg [Design fires in passenger trains], Swedish Transport Administration, Borlänge, 2014.
8. White, N. & Dowling, V.P., Conducting a Full-scale Experiment on a Rail Passenger Car, 6th Asia-Oceania Symposium on fire Science and Technology, Daegu, 2002.


Fire Safety Assessment in Europe – Process of Approval

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ABSTRACT
One of the main safety features for rolling stock, tunnels and stations is the safety of passengers, staff and third parties during an event of fire. This scope is the same all over the world. The fire safety requirements in order to reach that scope are not yet completely harmonized but a big step has already been taken. The applicable European rules and standards for fire safety in rolling stock are mainly characterized by:
• TSI SRT (rolling stock and infrastructure)
• EN 45545 (fire safety in rolling stock).
In order to be on the safe side considering product liability the railway operator as well as the railway supplier needs to investigate the actual state of technology. Thereby it might be necessary to follow further regulations or standards for vehicles or infrastructure.

With the publication of the EN 45545 a big step for a harmonization of requirements has been taken. Since August 2013 all parts (1 to 7) of the fire safety standard EN 45545 “Fire protection on railway vehicles” are published. This European Standard is supposed to get the status of a national standard in each European member state, either by publication of an identical text or by endorsement. For e.g. in Germany the national fire safety standard DIN 5510 shall be withdrawn at the latest by March 2016.

Above the EN 45545 the TSI SRT defines fire safety requirements for vehicles and for the tunnel infrastructure. Conformity to the TSI and therefore to the EN 45545 does not constitute per se a guarantee for sufficient safe operation inside a railway tunnel. Operators of railway vehicles have to verify, whether the train which is supposed to enter in public service meets the state of the technology requirements and if there are additional national requirements. For this purpose, a risk analysis should be applied.

That is even more necessary, as soon as „old“-tunnels (tunnels which were built before the TSI SRT was published) or “old“-vehicles are investigated.

In order to examine the fire risk and to find a justified decision that all fire safety actions are sufficient in order to meet the acceptable remaining risk it is necessary to follow a clear safety process e.g. as described inside the EN 50126.

KEYWORDS:
Fire safety assessment in Europe, technical specification for interoperability (TSI), risk based approach, comparison of fire safety requirements worldwide, compensation

1 INTRODUCTION
Rolling stock approval processes in Europe have tremendously changed during the last decade. That also involves the fire safety assessment. Harmonization of European railways as well as experiences in accidents and incidents contributed to this evolution. Various institutions or bodies took over new responsibilities and the standards and regulations were developed.
2 RETROSPECTION TO RAILWAY HISTORY IN EUROPE

Railway Traffic in Europe has not always been the way it is nowadays. Although European Member states are united in order to focus common strength and to cope with common threats each member state is independent and run autonomously.

The national railway networks have evolved from national needs depending on specific historical background influenced by national designs. This led to different, most of the time incompatible signaling systems, different electrical power supplies, different fire safety requirements (e.g., fire extinguishers) for rolling stock vehicles. But also communicating with dispatchers, signalers or other operational staff was rather complicated due to different spoken languages and carried a high potential of misunderstanding and in consequence for hazardous situations like fire incidence no one wanted to be responsible.

The theoretical and pragmatic idea of just harmonizing the networks failed due to commercial and economical interests and the almost impossible decision whose “requirements” to fulfill the safety targets is state of the art and who shall change accompanied by the question how to finance such a project.

Instead of that a migration strategy was agreed in 1996 among the member states to harmonize the (railway) traffic in a long term approach and to start with so called corridors (Trans-European Network - TEN) which form more or less multiple straight lines from one end of Europe to the other. Later a new TEN-T network (Tran-European Transport Network) idea started. The Trans-European Transport Networks (TEN-T) are a planned set of road, rail, air and water transport networks in the European Union. The TEN-T networks are part of a wider system of Trans-European Networks (TENs), including a telecommunications network (cTEN) and a proposed energy network (TEN-E or Ten-Energy).

In 2011 the European Commission set up a recommendation on the authorization for placing in service of structural subsystems and vehicles under directive 2008/57/EC (Interoperability directive). Stakeholders and bodies were introduced and their expected work during the approval process described. The recommendation was directed to each member state within Europe in order to harmonize from a technical perspective as well as processes, procedures, certificates and outputs.

3. RISK ASSESSMENT (RA) ACCORDING TO COMMON SAFETY METHOD (CSM)

Safe integration of subsystems (e.g., safe integration of Rolling Stock Vehicles into the railway network) also requires to control possible hazards and to apply mitigation measures following risk acceptance principles. Among the European member states national risk management was carried out in a way necessary comparison to harmonize safety levels was almost impossible. The European Safety Directive (2004/49/EC) demanded a set of common safety methods in order to cope with this deficiency. One of these Common Safety Methods was dedicated to Risk Evaluation and Assessment and first published as a European Regulation in 2009 (352/2009/EC). Multiple amendments and improvements were included in the follow-up regulation in 2013 (402/2013/EC). European Regulations are directly valid and not have to be transferred into national legislation, like European directives or recommendations. The Regulation describes a rather generic risk management process, applicable for all subsystems and stakeholder and defines the scope for independent safety assessment.

4. Risk Management Process according to EC regulation (402/2013/EC)

The EC Regulation on Common Safety Methods for Risk Evaluation and Assessment (402/2013/EU) introduces a new role called “proposer”, which in most cases for rolling stock approvals is taken on by the applicant.

Fig. 1  Risk Evaluation and Assessment acc. to CSM
The proposer is in charge of implementing and following a risk management process, as shown in figure 7, including hazard identification associated with the system under approval, the risk estimation based on identified hazards and choosing adequate risk acceptance criteria. Following risk evaluation to justify whether hazards can be sufficiently mitigated according to chosen criteria using safety measures will lead to implementation and verification. The correct implementation of this risk management process as well as the verification of sufficient implementation in order to mitigate identified risk is in charge of the independent assessment body also introduced by the European Regulation.

4.1 Independent Assessment Bodies
According to the regulation (402/2013/EU) assessment body means the independent and competent external or internal individual, organization or entity which undertakes investigation to provide a judgment, based on documented evidence, of the suitability of a system to fulfill its safety requirements.

An assessment body shall carry out an independent assessment of the suitability of both the application of the risk management process and of its results. This assessment body shall meet the criteria listed in the annex II of regulation (402/2013/EU).

4.2 Assessment Activities and Certification
According to (402/2013/EU) the assessment body shall ensure it has a thorough understanding of the significant change based on the documentation provided by the proposer and conduct an assessment of the processes used for managing safety and quality during the design and implementation of the significant change, if those processes are not already certified by a relevant conformity assessment body. In addition it shall conduct an assessment of the application of those safety and quality processes during the design and implementation of the significant change. Having completed its assessment in accordance with points above, the assessment body shall deliver the safety assessment report to the applicant (aka proposer). Duplication of work between the conformity assessment carried out by a notified body or a designated body shall be avoided.

5. Fire Safety Assessment
One of the main safety features for rolling stock, tunnels and stations is the safety of passengers, staff and third parties during an event of fire. This scope is the same all over the world. The fire safety requirements in order to reach that scope are not yet completely harmonized but a big step has already been taken. Up to the end of the nineties the complete normative process for fire safety standards was led by national standards and processes, only partly involving international authorities like the regulations of the Union Internationale des Chemines de fer (UIC). This process led to adjustments and modifications which involved the field of fire safety in rolling stock.
The big step for a harmonization of requirements was the publication of the EN 45545. Since August 2013 all parts (1 to 7) of the fire safety standard EN 45545 “Fire protection on railway vehicles” were published. This European Standard is supposed to get the status of a national standard in each European member state, either by publication of an identical text or by endorsement. For e.g. in Germany the national fire safety standard DIN 5510 shall be withdrawn at the latest by March 2016.

The following chapters give detailed information on the approval process regarding fire safety assessment. Above the EN 45545 the TSI SRT defines fire safety requirements for vehicles and for the tunnel infrastructure. The TSI SRT refers explicitly to the EN 45545-2 in order to specify requirements for fire behavior of materials and components. The other parts are named inside the TSI SRT only as recommendations.

5.1 Applicable harmonized Specification for Fire Safety – TSI SRT

The applicable European rules and standards for fire safety in rolling stock are mainly characterized by

- TSI SRT (vehicle and infrastructure)
- EN 45545 (fire safety in rolling stock).

In order to be on the safe side considering product liability the railway operator as well as the railway supplier needs to investigate the actual state of technology. Thereby it might be necessary to follow further regulations or standards for vehicles or infrastructure. The following conditions are given for the application of the TSI SRT:

- valid for tunnels longer than 1 km up to 5 km that means a travel time inside a tunnel of less than 4 minutes
- tunnels longer than 20 km require a special safety investigation that means a travel time above 15 minutes
  - 15 minutes are justified regarding the fire barrier verification. It is not possible to build a vehicle which has a system (fire barrier or fire containment and control system) that allows people to stay inside a vehicle during a fire event for more than 15 minutes
- applies only to new tunnels (new tunnel also consider that new vehicles)

Conformity to the TSI does not constitute per se a guarantee for sufficient safe operation inside a railway tunnel. Operators of railway vehicles have to verify, whether the train which is supposed to enter in public service meets the state of the technology requirements and if there are additional national requirements. For this purpose, a risk analysis should be applied. That is even more necessary, as soon as “old”-tunnels (tunnels which were built before the TSI SRT was published) or “old”-vehicles are investigated. In order to examine the fire risk and to find a justified decision that all fire safety actions are sufficient in order to meet the acceptable remaining risk it is necessary to follow a clear safety process e.g. as described inside the EN 50126.

5.2 The risk based approach

The process of the EN 50126 is targeted in order to define the requirements for the railway vehicle, infrastructure or sub-components. That takes place on the base of a risk analysis; refer to Figure 9 step 3 according to that analysis the requirements are implemented inside the investigated system. Finally that will be assessed of an independent authority.
The approach of a risk analysis is to find out with which effort the safety target and the specific safety requirements are fulfilled. Thereby the focus lies on the different “actions” (barriers) to prevent a fire hazard. The consequence (a starting fire) can be reduced through different barriers, refer to figure 9 (right). Inside the EN 50126 risk evaluations and acceptances are presented in order to answer the question which barriers should be realized in order to have an acceptable remaining risk. Risk acceptances should be based on generally accepted principles. For example the principle: As Low As Reasonably Practicable” (ALARP-principle). The Risk exceeding the limiting Risk must be prevented by measures in a reasonable way. The system must remain economical.

5.3 Methodology of fire risk analysis
The main objective of the fire analysis is to identify the fire hazards to the vehicle in case of fire. Fire is an exothermic process between fire load and an oxidation agent that produces heat and light. The requirements for a fire comprise four parameters: ignition source (energy), fire load, an oxidation agent, and the correct proportion between the fire load and oxidation agent. If any one of these parts is taken away a fire cannot exist. This usually is taken into account in fire risk analysis. For example a fire risk analysis can be based on the principle of a qualitative approach, as described inside the EN 50126:2006. In that case the fire risk analysis is evaluating parameters like:

- the probability,
- the severity and
- the probability of detection

In order to judge the parameters it is helpful to quality them by so called risk priority numbers (RPN) and when the calculated risk priority number is higher than a defined threshold further measures for risk reduction have to be made.

$$RPN = \text{probability of occurrence} \times \text{severity} \times \text{probability of detection}$$
Another example for a risk analysis is to use the risk graph according to the IEC 61508-5:2010. The Figure 12 gives an example of a risk graph.

**Steps to categorize the risk potential with the risk graph**

### 5.4 National variations for fire safety requirements

As already explained in the chapters above the harmonization process in Europe also for fire safety requirements is not finished yet. Due to the specific historical infrastructure development in Europe there are still national specific requirements which are explicitly listed inside the TSI.

For example Italy has a lot of long tunnels which where build before the TSI was developed. Therefore they declared a Decreto Ministeriale, DM for “Safety in Railway tunnels”, which applies to rolling stock running in railway tunnels which length reaches at least 1000 m and defines the requirements of active fire fighting systems for protection of technical and passenger areas. That means, in order to reduce the analyzed risk of a fire inside one of the old tunnels Italy stated that it is not economic to modernize the tunnels in order to meet the TSI requirements. Therefore every train running through Italy must have an active fire fighting system on board in order to meet the fire safety standard in tunnels. That specific requirement is allowed by the European railway authority and listed inside the TSI SRT:

> **“Specific case Italy (“T”):**
> Additional specifications for units intended to be operated in the existing Italian tunnels are detailed below.
> **Fire detection systems**
> In addition to the areas specified in the TSI, fire detection systems shall be installed in all passenger and train staff areas.
> **Fire containment and control systems for passenger rolling stock**
> In addition to requirements of the TSI, units of category A (tunnel longer than 1 km) and B(tunnels longer than 5km) passenger rolling stock shall be equipped with active Fire Containment and Control Systems. Fire Containment and Control Systems shall be assessed according to the notified National. …"

### 5.5 General Concept of safety barriers – practice example

Practice example: An underground moving train in a city.

Side conditions which need to be considered:

- high successions of trains with a lot of passengers
- stations with limited capacity and over some underground-levels
- fire risk might come from the vehicle (technical area or spurious action)
Discussion: The vehicle concept including the fire load depending on the initiated fire hazard create the measure of damage. The hazard of that damage has to be restricted if it is not possible anymore to evacuate the passengers and staff (self and foreign rescue) out of the vehicle and the stations. The smoke development is the most dangerous part of a developing fire. Therefore it has to be analyzed which barriers need to be implemented in order to guarantee a safe evacuation.

Possible Realization:

- fire resistant and non toxic (while burning) fire load inside the vehicle with low smoke development
- active or passive fire fighting in order to reduce the fire event
- smoke flares in the stations (beside the vehicle or at the upwards stairs)
- active smoke outlets at the stations or in the tunnel

For investigation on the fire barriers the actual state of regulations and technology should be taken into account and as well a detailed risk evaluation. For the investigating and analyzing process independent authorities and consultants are able to support in the best and practicable way since a risk oriented approach should be based on experience and expertise.

6. Summary and Outlook
The placing in service of rolling stock vehicles in Europe requires authorization based on approvals focusing the fire safety requirements. Different stakeholder and actors have been introduced and relevant directives, regulations and standards referenced. The correct application of risk management processes as well as the verification of the fulfilment of resulting safety requirements will be assessed by the safety assessment body. Concluding an example for fire safety is shown to fortify the applicability of the European approach. Today the European Commission gains experience and further harmonization is taking place. Reducing the remaining national differences and therefore notified national technical rules as far as possible is one of the remaining major challenges for the future.

REFERENCES
- EN 45545:2013 Railway applications - Fire protection of railway vehicles - Part 1: Requirements for fire behaviour of materials and components, August 2013
- EN 45545:2013 Railway applications - Fire protection of railway vehicles - Part 2: Requirements for fire behaviour of materials and components, August 2013
- EN 45545:2013 Railway applications - Fire protection of railway vehicles - Part 4: Fire safety requirements for rolling stock design, August 2013
- EN 45545:2013 Railway applications - Fire protection of railway vehicles - Part 5: Fire safety requirements for electrical equipment including that of trolley buses, track guided buses and magnetic levitation vehicles, August 2013
- EN 50126-1:1999 Railway applications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)
- 1303/2014/EC, 2014, Commission Regulation (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to ‘safety in railway tunnels’ of the rail system of the European Union,
Passenger Locomotive Fuel Tank Integrity Research

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ABSTRACT

The Federal Railroad Administration sponsors research on safety topics to address and to improve safety regulations and standards. This paper focuses on the latest research conducted to evaluate passenger locomotive fuel tank integrity. Fuel tank integrity standards exist to set a minimum level of protection against an impact to the fuel tank that might puncture the tank and cause the release of diesel fuel. As seen in numerous accidents in the United States (US) including Mebane, North Carolina in 2010, Goodwell, Oklahoma in 2012, Hoxie, Arkansas in 2014, and Concord, MA in 2010, breach of fuel tanks in train collisions and derailments may pose a risk to passengers and crew if fuel is ignited. The outbreak of a fire can inhibit the emergency egress of passengers and crew in passenger trains or cause injuries and fatalities due to exposure to the fire.

Throughout the US, where highways are at capacity and commuters are looking for more economical and eco-friendly means of transportation, many cities are expanding existing or planning new commuter rail lines. This trend has created a niche market for an alternative to conventional locomotives which has given rise to the use of self-propelled vehicles that operate in short consists over short routes. These alternate vehicles allow for easier reconfiguration of a train length in typical operation, as each railcar can be used to operate the entire consist. Diesel Multiple Units (DMUs) are a common type of self-propelled vehicle, for which each railcar has its own power supply with a diesel fuel tank mounted on the carbody. In comparison to trains led by a conventional locomotive, in DMUs the passengers are in closer proximity to the fuel tank, thereby enhancing the risk profile in the event of puncture of the fuel tank and subsequent fire.

Code of Federal Regulation (CFR) requires that Tier I (operations at speeds of 125 mph and less) locomotive fuel tanks have minimum structural properties adequate to sustain a prescribed set of static load conditions. Currently, these requirements apply to all equipment defined as a locomotive. In the US a single set of fuel tank standards applies to both freight and passenger locomotives, including alternative locomotives, such as DMUs. As such, the Federal Railroad Administration’s Office of Research and Development is conducting research into passenger locomotive fuel tank crashworthiness to determine how well existing regulations for conventional fuel tanks apply to alternative fuel tanks. Current research is intended to increase understanding of the impact response of fuel tanks under dynamic impact conditions and propose strategies for DMUs to meet a minimum level of safety. Analyses and preliminary testing, including full-scale dynamic impact tests of tanks, are underway. This paper reports the preliminary findings of test results, describes future plans for testing and discusses development of fuel tank standards for DMUs.

To date, a preliminary series of impact tests have been performed to measure fuel tank deformation under a dynamic loading conditions for a set of conventional locomotive fuel tanks. A complementary set of impact tests are planned for an alternative passenger locomotive (DMU) fuel tank. This paper describes the results of the first set of blunt impact tests for three retired EMD F-40
locomotive fuel tanks. These tests highlight how existing designs respond to a dynamic impact and helped identify the key design features that affect puncture resistance, e.g. size, shape, baffle configuration, stiffener placement, material properties, etc. The tests also set forth a repeatable methodology for further testing of fuel tanks.

**KEYWORDS:** locomotive fuel tanks, puncture resistance, full-scale testing, diesel multiple unit

**INTRODUCTION**

**Background**

The Federal Railroad Administration is responsible for the regulation of rail equipment operating on the general railroad system in the United States. To fulfill these responsibilities the FRA is organized into various departments including the Office of Safety, which promotes and regulates safety throughout the Nation’s rail network, and the Office of Research and Development, which ensures the safe, efficient and reliable movement of people and goods by rail through basic and applied research. The FRA Office of R&D has numerous research projects underway to address fire-safety related topics in passenger trains. The FRA Fire Safety Research program investigates technologies that can reduce the risk of a fire event in passenger rail equipment, and in the event of a fire allow for timely and safe evacuation of passengers and crew to a safe location away from the fire.

**Historical Context of Locomotive Regulations and Standards**

The purpose of the standards is to prevent the tank from failing catastrophically when challenged either in operation or in a common derailment or collision event and prevent leakage of fuel.

Locomotive fuel tanks, whether on a freight locomotive, a conventional Tier I passenger locomotive, or a Tier I DMU, are subject to structural requirements in the form of Federal Regulations [1,2] and industry standards (i.e., Association of American Railroads (AAR) Standard S-5506 [3] and American Public Transportation Association (APTA) Standard SS-C&S-007-98 [4]). Each of the existing regulations and standards requires the fuel tank integrity withstand as series of load cases, each correlated with an idealized load requirement a fuel tank could experience in a collision or derailment scenario of concern. A pass-fail criterion is defined for each load case and must be analyzed typically via a hand-calculation or finite element analysis by the locomotive manufacturer. The three scenarios prescribed in the regulations and standards are: minor derailment, jackknifed locomotive, and side impact. There is an additional design requirement intended to provide a minimum level of penetration resistance through a combination of material thickness and strength. Additionally there is a requirement for the valves and fittings to be flush with the tank. Protection of the fill controls is encouraged to be considered but no specifics are defined. While the load cases are substantially similar across all three regulations, there are minor differences in the way the loads are applied in each standard or regulation. Table 1 lists a summary of the requirements prescribed in the CFR.

<table>
<thead>
<tr>
<th>Table 1. Summary of CFR Requirements</th>
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<tbody>
<tr>
<td><strong>Load Case</strong></td>
</tr>
<tr>
<td>1 – Minor Derailment</td>
</tr>
<tr>
<td>2 – Jackknifed Locomotive</td>
</tr>
</tbody>
</table>
3 – Side Impact

A 200,000 pound load at the longitudinal center of the tank distributed over an area of six inches by forty-eight inches at a height of thirty inches above the rail. Without exceeding the ultimate strength of the material.

4 – Penetration Resistance

- The minimum thickness of the sides, bottom sheet and end plates of the fuel tank shall be equivalent to a 5/16-inch steel plate with a 25,000 pounds-per-square-inch yield strength (where the thickness varies inversely with the square root of yield strength).
- The lower one third of the end plates shall have the equivalent penetration resistance by the above method of a 3/4-inch steel plate with a 25,000 pounds-per-square-inch yield strength.

The APTA standards are similar to the AAR/FRA requirements except they cite more details for evaluating each load case and also list exceptions for load cases if the manufacturer can show other evidence indicating that that case will not occur. In some standards the manufacturer is allowed to take into account the surrounding structure and the placement of the tank.

Within the CFR, the term locomotive is defined in both 49 CFR 229.5 and 49 CFR 238.5. [1,2] In both cases, a locomotive is defined to include equipment that has an operating compartment and propelling motor and is designed for moving other rail equipment, either freight or passenger. This definition thus extends to freight locomotives, passenger locomotives, and other self-propelled rail equipment. A common type of self-propelled rail equipment is DMU equipment, which is more comparable in weight to a passenger car than a conventional locomotive. Because a DMU is defined as a locomotive in the CFR, DMUs must comply with all regulations applicable to conventional passenger locomotives.

**Diesel Multiple Unit Equipment**

A piece of DMU rail equipment is a self-propelled passenger rail vehicle with an onboard diesel engine. This type of rail vehicle, capable of generating its own motive power, can thus operate without the need of a dedicated, conventional locomotive. DMU vehicles may either be operated as a single vehicle or combined into a consist of multiple DMUs, each capable of powering itself. The DMU offers several advantages over conventional locomotive and coach passenger operations, including faster acceleration and deceleration times, potentially lower start-up costs, and increased operational flexibility. As mentioned earlier, under the current Tier I regulations in 49 CFR 238.233, a DMU is classified as a locomotive, and is therefore subjected to the same requirements as a conventional, non-passenger carrying locomotive.

Because of these advantages, several commuter rail services in the US have acquired or announced plans to acquire DMU equipment. Several recent commuter rail operations to use DMU service are summarized in Table 2. Each operation has either procured DMU equipment that was designed to comply with the applicable regulations, or has applied for and received a waiver of one or more applicable regulations from FRA.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Start-up Date</th>
<th>Equipment Manufacturer</th>
<th>Compliant or Waiver</th>
</tr>
</thead>
</table>
As Table 2 shows, current DMU operations in the US use a variety of designs that comply with the CFR and designs that are operated under a waiver of a particular CFR requirement. For these particular operations occurring under a waiver, the vehicles have received a waiver of the existing Tier I fuel tank requirements in 49 CFR 238.223.

The railroad environment in which a DMU operates may be substantially similar to the environment in which a conventional passenger locomotive is operated. If this is the case, then many of the hazards which exist for the fuel tank on a passenger locomotive may also exist for the fuel tank on a DMU. However, there are several details of DMU operation which may affect the overall risk of fuel tank puncture on a DMU.

DMU equipment typically carries less fuel than a conventional locomotive. According to Tofani and Walker, DMUs currently in operation within the US have a fuel tank capacity of 250–600 gallons, while a typical passenger locomotive fuel tank has a capacity of 1,800–2,500 gallons. Because of the smaller amount of diesel fuel carried onboard a DMU, a diesel fuel spill from a DMU fuel tank may have less severe consequences than a diesel fuel spill from a conventional fuel tank. In a DMU the passenger area is located on the DMU as oppose to conventional locomotives which pull passenger cars. However, because a DMU has the potential to carry more people than a conventional locomotive, there is a need to weigh the consequences of a fire in proximity to more people against the decreased risk that comes from carrying less fuel.

An additional issue related to the capacity of the fuel tank and its proximity to more people is the actual location of the fuel tank on the vehicle. On a typical passenger locomotive, the fuel tank is suspended beneath the underframe of the locomotive, adjacent to a truck and/or other pieces of underframe equipment. This placement renders the fuel tank exposed to loading both from a side impact (e.g., a highway vehicle at a grade crossing, or a raking impact), or from a detached piece of underframe equipment (e.g., a detached truck) for a sufficiently severe accident.

With the DMU designs surveyed in Table 2 it is less apparent that there is a “typical” placement for the fuel tank on these vehicles. A DMU fuel tank has a smaller capacity than a conventional locomotive fuel tank and there is additional flexibility offered to the manufacturer in terms of fuel tank placement. While generally, the fuel tanks are located low on the vehicle (e.g., beneath the underframe), the exact placement varies from DMU to DMU. DMU fuel tanks may be located inboard of the side structures of the underframe, potentially offering protection from a direct side impact into the tank. Dedicated shielding structures may also be used in an effort to prevent direct impact with the surface of the fuel tank.

**Accident Survey**

As a part of this research program, surveys of damage to locomotive fuel tanks resulting in puncture and loss of fuel have been conducted. Additionally, field examinations of damaged fuel tanks have been conducted for a bottom impact and a raking impact. The purpose of these field examinations was to determine causes of fuel tank ruptures and evaluate existing fuel tank designs.
These two field examinations, as well as the conclusions developed, are described in this section.

In extreme situations like the accident that occurred March 15, 1999 in Bourbonnais, IL in which an Amtrak train, with 207 passengers and 21 employees on-board struck and destroyed the loaded trailer of a tractor-semitrailer combination that was traversing the grade crossing. [12,13,14] Both locomotives and 11 of the 14 cars in the Amtrak consist derailed. The derailed Amtrak cars struck 2 of 10 freight cars that were standing on an adjacent siding. The second locomotive’s spilt fuel migrated underneath the sleeping car which then ignited. The accident resulted in 11 deaths and 122 people being transported to local hospitals. Collision conditions can provide a source of ignition that when coupled with spilt fuel can lead to fire. The passengers and crew emergency egress may be further inhibited in such situations.

Figure 1. Photo of passenger train in Bourbonnais, IL

The following are recent accidents investigated by the authors that highlight the specific puncture patterns experienced by fuel tanks in common operating or collision incidents. These results have been used to inform the full-scale testing research program.

Bottom Impact: Concord, MA, September 5, 2010
On Sunday, September 5, 2010, a Massachusetts Bay Transportation Authority (MBTA) locomotive struck debris on the track, puncturing the bottom sheet of the locomotive’s fuel tank. [15] FRA Region I personnel and Volpe staff conducted an examination of this locomotive fuel tank at MBTA’s Somerville, MA, locomotive shop. The locomotive involved in this incident was an F-40 type locomotive with a fuel tank of similar construction to tanks 232 and 234 used in the impact testing program. This locomotive was constructed in the late 1970s, including this fuel tank. The fuel tank involved in the puncture is shown in Figure 2 after removal from the locomotive.
Examination of the fuel tank revealed a single puncture to its bottom sheet in the center lobe toward the leading end of the fuel tank. From marks on the bottom of the tank, it appeared that the struck debris scraped along the bottom surface of the tank until encountering the change-in-stiffness adjacent to the baffles, when it caused a puncture. This puncture occurred adjacent to both a longitudinal and a lateral baffle, as Figure 3 shows. The damaged area also includes scuff marks on the bottom of the lateral baffle, indicating apparent contact either between the struck object or the punctured bottom sheet and this baffle.

From examining the size and the shape of the punctured bottom sheet as well as discussions with MBTA personnel, it appeared that the puncture was caused by a joint bar which had been placed upon the track by vandals. Figure 4 shows an exemplar joint bar compared with the puncture. Unfortunately, it is not known at what speed the locomotive was traveling when this incident occurred.
Raking Impact: Oak Island Yard, NJ, April 28, 2012

On April 28, 2012, a raking impact collision occurred at Oak Island Yard in Newark, NJ. In this incident, two locomotives rolled into a switch while the trailing end of another freight consist was still passing through. Figure 5 shows a diagram of the accident. The freight consist that was traveling through the switch was moving at approximately 7 mph and the rolling locomotives were moving at approximately 4 mph at the time of collision. As a result of this collision, the lead locomotive’s fuel tank (manufactured in 1977) was ruptured and the spilled diesel fuel ignited, resulting in a fire and damage to the leading locomotive.

The last five cars of the moving consist struck the locomotives, and the door track on the last boxcar tore a gash into the locomotive fuel tank along nearly its entire length. Figure 6 shows this boxcar after the collision, with the missing length of door track indicated. The inset image shows the fractured end of the door track which remained attached to the boxcar.
The door track struck the trailing end sheet of the lead freight locomotive, but did not puncture this sheet. The end sheet deformed, and the force on the end sheet appears to have buckled the side sheet, causing it to bulge outward. The door track then punctured the buckled portion of the side sheet as the boxcar continued to move past the locomotive. Figure 7 shows the trailing end of the punctured fuel tank.

The door track tore through several baffles and tore the lead end sheet away from the side sheet of the fuel tank. The portion of door track that had been torn away from the boxcar was found inside the lead locomotive’s fuel tank. Figure 8 shows the torn side sheet and the lead end sheet. As can be seen in this image, the lead sheet itself did not tear. The separation occurred either through tearing of the side sheet or the weld between the side sheet and the leading end sheet.
RESEARCH DESCRIPTION

FRA’s current research on fuel tank integrity was derived from the results of the accident investigations and surveys. The accidents show that fuel tank punctures can occur on any exposed location of the tank by a variety of impacting objects, including front or rear impact by an adjacent component as it detaches in an event, a side impact or bottom impact by a rigid part of another rail vehicle in the event of a rollover, a side-swiping impact with another train or railcar, or a direct impact by a piece of debris. Each scenario is categorized by its resultant loading type and in general there are two loading conditions leading to punctures: blunt impacts and raking impacts. [12]

There is no related set of standards in Europe or Asia that addresses fuel tank integrity. The only applicable requirement for fuel tanks is an attachment strength requirement in EN12663 [17]. The lack of foreign standards governing imported fuel tanks and the difference in risk environment between conventional locomotive fuel tanks and fuel tanks on DMUs are two motivating factors for FRA’s current research program into the puncture resistance of fuel tanks.

Full-scale Testing of Fuel Tank Integrity

FRA has conducted a series of impact tests and analyses to characterize the behavior of locomotive fuel tanks when subjected to a blunt impact on their bottom surfaces. [18,19] These tests have established a repeatable test setup (e.g. support conditions, instrumentation requirements, etc.) which can also be used to perform impact tests on DMU fuel tanks. These tests conducted to date utilized fuel tanks from retired passenger locomotives that had been donated to FRA as test articles.

The three fuel tank test articles are shown in Figure 9. These fuel tanks were referred to by the numbers assigned to their parent locomotives, i.e. tank 202, tank 232, and tank 234. Each tank had approximately a 6,810 L (1,800 gallon) capacity. While all three tanks were removed from similar F-40 type passenger locomotives, each of the fuel tanks was of a unique design. Tanks 232 and 234 had approximately the same outer shell dimensions and plate thicknesses, but each featured a unique arrangement of internal baffles. Tank 202 was of an entirely different design, featuring squared-off sides and a unique baffle arrangement of its own. The left column of this figure shows a photograph of the actual tank. The center column shows an inverted view of the tank’s exterior, taken from the finite element (FE) model. The right column of this figure shows the baffle arrangement within the FE model of each tank.
In the testing program, the fuel tanks were removed from the locomotives and mounted to a rigid, vertical wall. The tanks were attached to the wall through the bolt holes that would normally be used to attach the fuel tanks to the underside of the locomotive during service. This mounting scheme approximates an impact condition that could occur if the locomotive were to have derailed and come to rest on its side, exposing the fuel tank to secondary impacts. Figure 10 shows the locomotive fuel tank mounted to the impact wall.

The fuel tank was struck by a dynamic impact vehicle equipped with a 30.5 cm x 30.5 cm (12 inch x 12 inch) ram head. An image of the impact vehicle is shown in the photo on the right of Figure 3. The impact vehicle was formerly used as a piece of maintenance-of-way equipment and has been modified to accommodate ram heads of different shapes and sizes. With the ram head installed, the impact cart weighed approximately 6,350 kg (14,000 pounds) for this test.

The primary results from the impact tests included the deceleration-time history of the impact cart and the deformation mode of the tank, including whether puncture occurred. Tri-axial accelerometers (i.e. vertical, lateral, and longitudinal) were installed on the impact cart at five locations. These locations included the leading-end cross member, the left and right side sills, the center cross-member, and the trailing-end cross member. A pair of speed sensors was mounted on the left and right side sills to
measure the speed of the cart just prior to impact. Each test was documented using high-speed and conventional-speed video cameras on the ground, and conventional-speed video onboard the impact vehicle.

The three blunt impact tests performed of conventional locomotive tanks are summarized in Table 3.

<table>
<thead>
<tr>
<th>Tank</th>
<th>Test Date</th>
<th>Impact Speed</th>
<th>Impact Energy</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>October 9, 2013</td>
<td>10 km/h (6.2 mph)</td>
<td>24 kJ (17,980 ft-lbs)</td>
<td>3.8 cm (1.5 inch) residual dent / No puncture</td>
</tr>
<tr>
<td>232</td>
<td>October 8, 2013</td>
<td>7.25 km/h (4.5 mph)</td>
<td>13 kJ (9,470 ft-lbs)</td>
<td>12.7 cm (5 inch) residual dent / No puncture</td>
</tr>
<tr>
<td>234</td>
<td>August 20, 2014</td>
<td>18 km/h (11.2 mph)</td>
<td>79.5 kJ (58,660 ft-lbs)</td>
<td>21.6 cm (8.5 inch) residual dent / No puncture</td>
</tr>
</tbody>
</table>

In each of the three tests it was found that the baffle construction plays a significant role in the structural response of the tank. As shown in Figure 2, the baffle configuration, shape, cut outs and attachment details can vary greatly between tanks. The baffle configuration and the attachment details, which are not guided by regulation had a significant influence on the deformation mode of each tank that was tested. Finite element analyses were used to further analyze the fuel tank integrity to the point of puncture. [18,19]

SUMMARY

The results of the three blunt impacts to passenger locomotive fuel tanks have provided valuable information on the impact response of the conventional fuel tanks, as well as on the details of construction that have an effect on this response. While the CFR requirements for puncture resistance require a combination of bottom sheet thickness and strength, these tests have demonstrated that the arrangement of internal baffles also plays a role in determining the puncture behavior of the fuel tank. While the baffles are typically intended to prevent fuel from sloshing within the tank, it may be important to also consider the structural influence of baffles to a tank’s puncture resistance when discussing the topic of fuel tank integrity.

The recent research on dynamic impacts of conventional fuel tanks provides some key results that can be transferred to inform the design of fuel tanks. Strategic construction of tanks can likely improve fuel tank puncture resistance. This research indicates that design planning should include careful consideration of material properties beyond the yield strength required in the regulations (e.g. higher-ductility materials may offer greater puncture resistance). Additional considerations that have come to the attention of the researchers through this program include the possible effects of baffle arrangement on puncture resistance. While it has not yet been tested in this program, external shielding of the fuel tank may also offer improvements to the puncture resistance of fuel tanks. Additionally, surveys of accidents show that strategic placement of the tank can aid in protecting the tank from impacts (e.g. placing carbody structural members between the side of the DMU and the tank).

The next steps in fuel tank research include full-scale testing of DMU tanks. FRA has procured three new fuel tanks typical of DMUs currently in use in the U.S. The first test will be conducted on a DMU in late June 2016. The test setup will follow the blunt impact test setup developed for the conventional fuel tank tests.

There are two key reasons prompting the review of standards for DMU fuel tanks. The first stems from the history of fuel tank regulations in the US, which were created for freight equipment and
adopted for passenger equipment. With the size of DMU fuel tanks nearly a tenth of the capacity of freight fuel tanks, applying existing requirements to DMU tanks is challenging and may not be appropriate. The second impetus for looking at DMU standards is the growing demand for DMU equipment in the US for small-scale passenger line expansions or start-ups desire flexible consist arrangements. Finally, with US passenger equipment manufacturers near-extinct, most new equipment is provided by European or Asian manufacturers. Equipment from foreign manufacturers must be made to demonstrate compliance with the CFR or a waiver must be submitted to FRA for consideration as “alternatively compliant”.

FRA’s research program is focused on establishing the technical basis needed to develop performance-based fuel tank standards, applicable to a range of designs. With the findings of this research and collaboration between the government-led researchers, the passenger rail industry and the passenger rail equipment manufacturers can next develop a set of requirements that ensure fuel tank integrity for alternative fuel tanks.

REFERENCE LIST
16. ASME papers on fuel tank tests

Heavy Truck Fireworthiness under Impact Conditions

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ABSTRACT

Heavy truck fires occur in crashes as well as from non-crash causes. The fires occurring in crashes are associated with a large number of large truck fatalities over the past 20 years. The design of fuel systems, the use of flammable materials, and high exhaust and emission control component temperatures contribute to the occurrence of fires.

KEYWORDS: fireworthiness, fuel system fires, heavy trucks

INTRODUCTION

There have been more than 2,465 heavy trucks fatalities with fires in the past twenty years. There have been 5,297 heavy truck fires in fatal crashes in the last twenty years. The United States has about 9 million large trucks with about 2 million of those being class 7 and 8. The number of long haul vehicles is expected to increase by about fifty percent by 2030. The typical fuel system places virtually unprotected fuel tanks in exposed positions outside the frame of these vehicles. The cab materials are no better designed than those of passenger vehicles and being above the fuel system can be exposed to flames leading to rapid flame spread. The fuel system is often packaged close to high temperature exhaust and emission control components. Their proximity in conjunction with failures under crash conditions may contribute to the ignition and spread of fires in large trucks.

Background

There have been about 5,300 heavy truck fires in fatal crashes in the last 20 years. Of those crashes, there were about 2,500 fatalities in heavy trucks with fires [1]. About 30-35% of the heavy truck fatal crash fires involved the fuel tank [2].

In the National Highway Traffic Safety Administration’s Large Truck Crash Causation Survey (LTCCS), fuel tank fires were all classified as major fires. Of these major fires, about 75% of the fuel tank fires involved another vehicle, while about 25% involved a fixed object [3].

A standard on heavy truck fuel systems (SAE J703) [4] was first issued in 1954. Currently this standard contains a pressure relief venting system test, a fuel tank assembly leak test, an air vent leak test, a drop test, and a fill pipe test. In 2000, another safety standard related to heavy truck fuel systems, SAE J1624 [5], was first issued. SAE J1624 defines a crossover line support test and an unprotected end test. It also concerns crossover lines used to connect liquid fuel tanks and equalize their liquid levels, pressure, and/or cause multi-tanks to function as one.

The United Nations adopted uniform vehicle regulations that were eventually revised to include several addenda, including Regulation No. 34, Uniform Provisions Concerning the Approval of Vehicles with Regard to the Prevention of Fire Risks [6] in 1958. Regulation No. 34 states that “tanks shall be installed in such a way as to be protected from the consequences of a collision to the front or rear of the vehicle [7],” and also calls for front, lateral, and side impact tests, with the rule that “no more than a slight leakage of liquid in the fuel installation shall occur on collision,” and “no fire
maintained by the fuel shall occur [8].” With the adoption in 1970 of Council Directive 70/221/EEC [9], the European Economic Community began regulating heavy truck fuel tanks. This required that heavy truck fuel tanks be installed such that they are protected from the consequences of front or rear impacts, but there was no mention regarding side impacts [10].

In 1970 Franchini [11] reported on crash tests where passenger cars struck stationary trucks fuel tanks in the impact area. The truck fuel tanks were deformed and displaced by the impacts; therefore Franchini suggested that truck fuel tanks should be located between frame side rails.

In 1971, The U.S. Department of Transportation Federal Highway Administration code part 393.65 and 393.67 were enacted to regulate fuel systems and fuel tanks for all motor vehicles, which included heavy trucks [12]. This code specifies that “Each fuel system must be located on the motor vehicle so that—(1) No part of the system extends beyond the widest part of the vehicle; (2) No part of a fuel tank is forward of the front axle of a power unit,” and that, “Each fuel tank must be securely attached to the motor vehicle in a workmanlike manner [13].”

In 1978 a report prepared for the NHTSA by Cassidy [14] showed that the incidence of fire/explosion in heavy trucks was much higher than that in other vehicles, and cited fuel tank placement as a potential contributing factor.

In 1988, Koppa et al examined the fuel system integrity loss in heavy truck accidents [15]. They examined a series of crashes in Texas and Arkansas that involved heavy tractor-trailers in which fuel spillage and/or fire occurred. They found that in 85% of the cases studied, fuel tank damage (crushing, denting, or displacement) occurred, while feedline damage and crossover line damage were far less common [16].

Hildebrand and Wilson [17] reported on their 3-year series of in-depth investigations of heavy freight vehicle collisions in 1997. In 10% of the cases studied, they found that the fuel tanks ruptured, either after a sideswipe-type collision, or after a rollover. The investigators wrote, “The typical location of the fuel (saddle) tanks leaves them exposed in the event of multivehicle collisions [18].”

NFPA had created draft versions of NFPA 556 in 2004 that “identifies major fire safety concerns associated with passenger road vehicles and provides guidance on methods and tools to decrease the their fire risks with the intent being to increase the likelihood that occupants will have time to exit or be rescued in case of fire. NFPA 556 provides guidance toward a systematic approach of the determination of the relationship between the properties of passenger road vehicles and the development of hazardous conditions in the vehicle. It presents a methodology that can be used in the selection of materials and design of components and systems, with the intent of providing a desired level of fire safety to occupants in passenger road vehicles in response to specific fire scenarios [19].”

In 2006, Ferrone and Sinkovits [20] set out to dispel a common misconception is that diesel fuel cannot explode and/or ignite upon a collision or impact. They found that spilled or atomized diesel fuel can ignite when there is an ignition source, such as a spark from the truck tractor battery box, which is frequently located within inches of a side mounted fuel tank [21]. In 2009, Ferrone [22] reported that atomized fuel from a breached fuel tank can be a cause of fire in heavy vehicles.

In a study from 2008, Ray [23] reported on fire rates for “large trucks” using NASS-GES data for 2000-2005 and found that the fire rates were about five times those for passenger vehicles. The definition of “large trucks” included both medium and heavy trucks and were defined as vehicles with GVWR greater than 10,000 pounds. The analysis of the LTCCS data showed that 34% of the data set they used involved hazardous materials (gasoline, propane, calcium carbide, molten sulfur, flammable solid) with 28% of the small sample having fires originating in the trailer, 24% originated at the fuel tank, and 14% in the engine compartment. Fire spread from another vehicle in one of the cases (6%).
Fuel tank placement was cited in 2001 by Bunn et al [24] as a reason why large trucks are more likely to catch fire in a collision than other types of vehicles. “Increased exposure occurs in large trucks because the two fuel tanks on the semi-tractor are exposed under the cab and are located directly behind the front axle. In light trucks and passenger cars, the fuel tank is typically placed above or in front of the rear axle. Thus the fuel tank is more protected in passenger vehicles and light trucks and is not as exposed as the fuel tanks on semi tractors [25].”

In 2011, an injury severity study from collected data from a nationally representative sample of large truck crashes by Zhu et al. [26] found that “crashes that result in fire also lead to more severe injuries [27].”

In 2012, a study by Pearlman and Meltzer [28] developed several relatable databases of reported truck fire incidents between 2003 and 2008, including records from the U.S. Fire Administration’s National Fire Incident Reporting System (NFIRS), FMCSA’s Motor Carrier Management Information System (MCMIS), and the National Highway Traffic Safety Administration’s (NHTSA) Fatality Analysis Reporting System (FARS) database, and found that Commercial Motor Vehicle fires are most common among GVWR Class 8 trucks.

In 2012, NHTSA’s study derived from data on large truck crashes found that [29], “large trucks were more likely to be involved in a fatal multiple-vehicle crash (as opposed to a fatal single-vehicle crash) than were passenger vehicles. 81% of fatal crashes involving large trucks are multiple-vehicle crashes, compared with 58% for fatal crashes involving passenger vehicles [30].”

**Examples of Heavy Truck Crashes With Fire**

*Figure 1. 2006 Freightliner tank*  
*Figure 2. Dump truck fatal fire*

Figure 1 illustrates a 2006 Freightliner ST120 ruptured tank. The Freightliner burst into flames.

Figure 2. (LTCCS case 813004906): A 1995 Ford F-700 truck dump truck which was carrying a full load of sand. A Buick impacted the truck and displaced the left front axle and struck the fuel tank. The driver of the Ford truck was completely burned from the vehicle fire and died at the scene.

Many more fire cases were studied but space limitations prevent their inclusion in this paper. In four heavy truck fire forensic cases examined, fires fatal to the occupants of the heavy truck all involved impacts with the diesel fuel tank; two were single vehicle impacts and two were vehicle to vehicle impacts. Of these three are known to have had ruptured tanks, with the fourth likely ruptured as well. Of the three LTCCS cases involving five trucks, three of the tanks were reported as having been ruptured.
Fire Rates under impact conditions

The fire rates under impact conditions observed in heavy trucks from 2001 to 2012 are determined and compared with the equivalent rates for passenger vehicles.

Data from NASS-GES system for 2001-2012 was used to compute the fire rates for heavy trucks and passenger vehicles. The results show that the probability of fire in a heavy truck in a crash is over eight times greater than the probability of a fire in a passenger vehicle in a crash. The difference in crash impact fire rates were statistically significant at the <0.0001 level.

The mean fire rate per 1,000 crashes for passenger vehicles was found to be 1.23 and 10.14 for heavy trucks, as illustrated in Figure 3. The 95% confidence intervals are from 13.14 to 7.14 for heavy trucks and 1.37 to 1.08 for the passenger vehicles.

The Effect of Alternative Fuel Tank Protection Design Approaches under Impact Conditions

It is of major importance to prevent the fuel system from rupturing during crash conditions. Examples of protective structures are in use, and suggestions have been made for placing the fuel tanks between the frame rails (or for providing other protective measures). These suggestions go as far back as 1969. Advanced Finite Element Modeling (FEM) methods for evaluation of heavy truck fuel tank impact protection have been identified. These have been shown to result in substantial reductions in fuel tank deformation and loading [31]. An example virtual testing matrix is shown in Table 1 [32].
Table 1. Virtual test matrix for use in Evaluating Heavy Fuel Tank Protection Designs

<table>
<thead>
<tr>
<th>Impact Mode</th>
<th>Impact Angle</th>
<th>Vehicle 1 Velocity (kph)</th>
<th>Vehicle 2 Velocity (kph)</th>
<th>Striking Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle-to-Vehicle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centered on tank</td>
<td>90</td>
<td>0</td>
<td>80</td>
<td>Midsize passenger car;SUV</td>
</tr>
<tr>
<td>Centered forward of tank</td>
<td>90</td>
<td>80</td>
<td>80</td>
<td>Midsize passenger car;SUV</td>
</tr>
<tr>
<td>Centered forward of tank</td>
<td>45</td>
<td>80</td>
<td>80</td>
<td>Midsize passenger car;SUV</td>
</tr>
<tr>
<td>Fixed Object</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset Barrier</td>
<td>5</td>
<td>89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal Barrier</td>
<td>0</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jersey Barrier</td>
<td>20</td>
<td>97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example results from the use of the test matrix are shown in Table 2 [33]. It shows potential improvements available from alternative heavy truck tank protection approaches. Alternative 1 has an additional frame rail surrounding the tank with a forward facing “ramp” for additional protection. See Figure 4.

Figure 4. Alternative 1

Figure 5 illustrates alternative 2 has a raised tank integrated with the frame rails and fitted with additional protective guards. Figure 6 is another example of an advanced frame.

Figure 5. Alternative 2
Figure 6. Example advanced technology frame for heavy truck fuel tank protection

Table 2. Virtual testing results.

<table>
<thead>
<tr>
<th>Impact Configuration</th>
<th>Percent Volume Reduction</th>
<th>Crush Energy Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tank Configuration</td>
<td>Percentage Compared to Baseline</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>Alternative 1</td>
</tr>
<tr>
<td><strong>Car to Heavy Truck</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 degree, both moving</td>
<td>75.9</td>
<td>4.6</td>
</tr>
<tr>
<td>90 degree, both moving</td>
<td>68.9</td>
<td>22.9</td>
</tr>
<tr>
<td><strong>SUV to Heavy Truck</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 degree, both moving</td>
<td>82</td>
<td>44.8</td>
</tr>
<tr>
<td>90 degree, stationary truck</td>
<td>76.3</td>
<td>17.3</td>
</tr>
<tr>
<td>90 degree, both moving</td>
<td>73.2</td>
<td>33.7</td>
</tr>
<tr>
<td><strong>Fixed Object</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 degree, 89 kph</td>
<td>39.2</td>
<td>4.0 *</td>
</tr>
</tbody>
</table>

* Alternative 1 with leading protective ramp

The use of frame systems that incorporate variations in width and depth expand the opportunities for protecting the tanks between the frame rails [34]. Another approach is a Tapered Frame Integrated (TFI) design. See Figure 6 [35].

Results from evaluation of this design approach compared to the baseline design, shown in Table 3 [36], demonstrate opportunities for significant improvement in fuel tank protection in heavy trucks.
Table 3. Improvements in fuel tank protection available with advanced technology frames.

<table>
<thead>
<tr>
<th>Impact Configuration</th>
<th>Tank Configuration Percent Volume Reduction</th>
<th>Percent Crush Energy Reduction from Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>TFI</td>
</tr>
<tr>
<td>SUV to Heavy Truck</td>
<td>82.0</td>
<td>0.8</td>
</tr>
<tr>
<td>45 degree, both moving</td>
<td>76.3</td>
<td>13.1</td>
</tr>
<tr>
<td>90 degree, stationary truck</td>
<td>73.2</td>
<td>6.5</td>
</tr>
<tr>
<td>Fixed Object</td>
<td>39.2</td>
<td>2.8</td>
</tr>
<tr>
<td>5 degree, 89 kph</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Review of Testing Methods for Material Flammability

In addition to protecting the fuel system it is clear that reductions in material flammability associated with the truck cabs would result in less rapid spread of the fires. Truckers are dying in crashes with very low impact delta-Vs due to the rapidity of the spread of fires into cabs.

Since the flammability of heavy truck materials likely contributes to the spread of a fire, it is clear that FMVSS 302 test methods are inadequate for use in the heavy truck environment. For example, the orientation of the material surface normal to the flame (horizontal) provides an unrealistic situation for the flame especially in heavy trucks where the fire will likely be coming from below the compartment. Test procedures with the material parallel with the flame (i.e. vertical) would be more representative as used in aircraft test procedures and other applications.

Instead of FMVSS 302 it is more realistic to use either UL 94 V-0 or NFPA 701 (both vertical tests) In addition, the cone calorimeter (ASTM E1354) should be used for assessment of ignition time and heat release. This measures properties that address realistic fire hazard as recommended by NFPA 556.

By 1988 Underwriter Laboratories UL94 [37] flammability test standard was accepted for use by U.S. Department of Defense. The flammability testing included provision for testing with the sample orientated in the vertical direction with classifications from HB, V-0, V-1, V-2, 5VB, 5VA for plastics and HF-1, HF-2, HBF for low density foams, and VTM-0, VTM-1, VTM-2 for films. The general distinction between classes cover burning rate, time till the flame goes out, and whether flaming dripping melt or holes are occurring.

In 1989, NFPA did a complete rewrite of NFPA 701 that was originally created in 1938 and revised over time. The testing measures the ignition resistance of material after it is exposed to a flame. The flame, char length, and flaming residue are recorded. The material will meet the requirements if all samples meet various criteria related to the flame going out quickly, the burn length being small and the material doesn’t continue to burn when reaching the floor of the test chamber.

In 1990 ASTM created E1354 (from P190) to provide a standard for cone calorimeter testing to determine the response of materials exposed to controlled levels of radiant heating with or without an ignition source [38]. Since radiant heat is the major cause of fire spread, the cone measures intensity of the peak rate of heat release (PRHR) and the speed to reach PRHR. Thus it is another way of determining the suitability of materials for use in life critical environments; it provides a way of evaluating realistic fire hazards as recommended in NFPA 556.

By about 2005 the UN and the ECE had adopted Regulation 118 that covered burning performance of vehicle materials. While it is called out as applicable to M3 and Class I and Class II vehicles since there are no other flammability requirements in Europe these are likely adopted for most vehicles.
An important aspect of this regulation is the inclusion of a vertical burning test to determine the vertical burning rate that must be below 100 mm/minute.

**Potential Fire Ignition Sources**

Ignition sources on heavy trucks include mechanical sparks, turbo chargers, exhaust and emission control system components, and large electrical battery compartments near the fuel system. The advent of emission control systems (that have been implemented since 2007) that may be in proximity to spraying or misting fuel from ruptured fuel tanks [39] or lines, suggest that care must be taken for the routing and protection of exhaust components. The placement of electrical batteries and wiring represent potential spark ignition sources in a crash [40]. Additional sources are known to be from sparks or other heat sources with atomized diesel fuel.

In 2001 the Environmental Protection Agency (EPA) established a clean diesel truck and bus program with significant focus on reducing heavy truck emissions with the introduction of technology between the 2007 and 2010 time frame. The technology used high efficiency catalytic exhaust emission control or similarly effective technologies. In general the added technology is implemented with a selective catalytic converter and diesel particulate filter. The technologies can involve surfaces with much higher temperatures than were previously present in the exhaust line and hence represent new potential ignition sources. While typically there are shields protecting these surfaces during normal operations, under crash conditions these protective measures may be violated and hence need to be taken into account during fireworthiness design approaches.

See Figure 7 for examples of heavy duty vehicle emissions control equipment required to reduce emission starting in the 2007-2010 timeframe. This equipment may lead to elevated surface temperatures.

![Figure 7. Examples of additional exhaust treatment technologies.](image)

**DISCUSSION**

As has been shown, the example fire cases underscore the importance of protecting the fuel system in heavy trucks. The existing fuel system protection test methods are clearly inadequate having generally been formulated decades ago and not providing the kind of protection that is required in today’s accident environment. The flammability of materials and fuel tank impact protection are inadequate as the fires that occurred were under conditions in which most if not all drivers did not die as a result of the impact itself.
CONCLUSION

Testing methods for heavy truck fireworthiness evaluations need to be improved.

The use of virtual testing methods can lead to improved fuel system protection at low cost. Protective design approaches exist and have been demonstrated with the available technology.

More rigorous materials flammability testing is essential. A vertical flammability test will help handle the subsequent effects of a fire. Reduction in flammability of tractor materials can be expected to result in longer times for drivers to exit the vehicle.

REFERENCES

1. GES, NHTSA, 2012
3. Ibid
7. Ibid, p. 11.
18. Ibid, p. 43.
27. Ibid, p. 53.
35. Ibid, p. 2.
Case Study of Recent Accidents Investigated by the NTSB
FIVE 2016

Joseph Panagiotou, Joseph Kolly
National Transportation Safety Board, USA

ABSTRACT
This paper discusses two recent accidents investigated by the National Transportation Safety Board (NTSB). The accident sequence of events, resulting injuries and details of vehicle fire damage are described. The resulting recommendations issued by the NTSB made to improve the fire safety of the vehicles involved are discussed.

The first accident [1] involved a fire following the collision between a tractor trailer and an National Railroad Passenger Corporation (Amtrak) passenger train. Major safety issues identified in this investigation were commercial driver fatigue and distraction, commercial driver license and employment history, commercial vehicle brake maintenance, passenger railcar crashworthiness and fire protection, and grade crossing action plans. The NTSB made recommendations to several organizations, including the Federal Motor Carrier Safety Administration, the National Highway Traffic Safety Administration, the Federal Highway Administration, and the Federal Railroad Administration.

The second accident [2] involved a fire following the collision between a tractor trailer and a motorcoach. This investigation identified the following safety issues: inadequate fire performance standards for commercial passenger vehicle interiors, pre-trip safety briefings for commercial passenger vehicles, improvements in commercial passenger vehicle design to facilitate evacuation, and event data recorder survivability for crash reconstruction and safety improvements. As a result of this investigation, the NTSB made recommendations to the National Highway Traffic Safety Administration and the Federal Motor Carrier Safety Administration.

KEYWORDS: fire doors, emergency exits, emergency lighting, egress, smoke filling, FMVSS 302

HIGHWAY-RAILROAD GRADE CROSSING COLLISION IN MIRIAM, NEVADA

Accident Narrative
On June 24, 2011, about 11:19 a.m. Pacific daylight time, a 2008 Peterbilt truck-tractor pulling two empty 2007 side-dump trailers (accident truck) was traveling north on US Highway 95 (US 95) near Miriam, Nevada, approaching an active highway–railroad grade crossing. This grade crossing consisted of two cantilever signal masts with flashing lights and two crossing gate arms. The accident truck driver had begun his shift at 2:30 a.m. and was on his return trip from the Esmeralda mine near Hawthorne, Nevada, to the John Davis Trucking facility in Golconda, Nevada. At this point in his trip, he had driven about 372 miles and had been on duty for almost 9 hours. About the same time, Amtrak train no. 5, a 2-locomotive 10-railcar train, approached from the northeast. A video camera mounted to the front of the train revealed that prior to reaching the grade crossing, located 3 miles south of Interstate 80 (I-80), the train was sounding its horn and the crossing gate arms had fully descended to block highway traffic. The locomotive event data recorder showed that the train was traveling 77 mph when the collision occurred. Tire marks at the accident scene began 349 feet south of the grade crossing, indicating that the truck driver had initiated a hard braking maneuver prior to striking the
train. The accident truck struck the tip of the south crossing gate arm and then the left side of crew sleeper railcar 39013, at a location about 222 feet behind the front of the train. The engine compartment of the truck-tractor penetrated and became lodged in the lower level of the crew sleeper railcar. The first side-dump trailer then detached and struck the first coach railcar 34033. Fuel from the accident truck ignited, and a fire ensued in the crew sleeper railcar, which spread to the two trailing coach railcars. (See figure 1.) The train did not derail, and the front of the train came to a stop about 3,117 feet southwest of the grade crossing.

A truck driver who had been traveling behind the accident truck stated that he saw the approaching train 0.25–0.5 mile before the grade crossing and started to slow his truck. He noticed that the accident truck was not slowing. He saw the grade crossing lights flashing and saw the crossing gate arms down. Prior to the crash, he saw the accident truck’s brakes lock up and saw “black smoke coming from the brakes.” Upon impact, the witness saw what he described as an explosion and fire. He saw “little spires of fire” all the way down the tracks to where the train stopped. By the time he arrived at the intersection, the tractor was “missing.”

![Figure 1](image)

**Figure 1** From left to right, photograph showing two locomotives, baggage railcar, burning crew sleeper railcar, first coach railcar with large opening where penetrated by first side-dump trailer, and front of second coach railcar. (Courtesy of rail passenger)

**Injuries**

The train was occupied by 14 Amtrak crewmembers and 195 passengers. The truck driver, the train conductor in the crew sleeper railcar, and four passengers in the first coach railcar were killed. According to the Washoe County medical examiner, all six deaths were caused by blunt force trauma. Five train occupants (four passengers and one crewmember) suffered serious injuries, such as fractures, lacerations, and burns. Eleven passengers received minor injuries, such as abrasions, contusions, and smoke and carbon monoxide inhalation.

**Vehicle Examination**

Three railcars were examined over the course of the on scene investigation. These cars, in the order of the train consist, were a transition sleeper car (car 39013), a double deck coach car (car 34033) and another double deck coach car (car 35006). The transition sleeper was impacted by the tractor trailer and the coach car behind it was impacted by a trailer. The third coach car did not receive any impact damage. The following sections describe the fire damage observed on the vehicles involved. The full fire investigation factual report can be found in the NTSB’s public docket [3].

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Car 39013

The transition sleeper car was a double deck car with employee sleeping accommodations on the upper level and a lounge/office and lavatories on the lower level, which were separated by the stairwell and luggage rack area in the middle of the lower level. The transition sleeper car was struck by the tractor trailer in the area of the leading wheel trucks. The tractor trailer did not penetrate the car at the location of the forward trucks but did penetrate just aft of them, tearing an opening along the lower level up to where the trailing wheel trucks begin (see figure 2). On the aft end of the car, the rubber seal surrounding the car-to-car door leading to the trailing car was completely consumed by the fire. The car-to-car doors are powered and have three modes of operation, selected by a switch on either side of the door. In normal mode, the door opens with a press of a button and then automatically closes about 15 seconds later. In manual mode, the door free wheels and can be slid open and closed manually. In the off mode, the door opens by pressing the button and then remains open until the button is pressed again. On the aft car-to-car door, the outer mode switch was in the normal position. The inner mode switch was missing, destroyed by the fire. The car had two separate air conditioning units, one in the forward equipment bay and one in the rear. The pleated fabric of the particulate filters on both air conditioning units were blackened, consistent with soot being drawn in. In the aft area of the lower level the tractor trailer’s engine was found resting near the right hand side (the non-impact side of the car). In the vicinity of the area where the engine was recovered, but more toward the left hand side of the car (the impact side of the car), remnants of the tractor trailer’s passenger side fuel tank were found. In this same area, fuel lines and a fuel pre-heater were also found. Additionally, steel belting, consistent with the remains of a tractor trailer’s tire, was also found in the same area.

Figure 2 Left side, aft portion of transition sleeper car 39013.

Car 34033

This coach car was behind the transition sleeper car. The coach had passenger seating and lavatories on the lower level which were separated by the stairwell and luggage racks. The entire upper level was passenger seating. The coach car had impact damage, which caused a large portion of the upper level sidewall from the leading edge of the coach to about the middle to rip and buckle leaving a large opening (see figure 3). This railcar was entirely burned out by the fire. The rubber seal surrounding the car-to-car door at the forward end of the coach car was completely consumed by the fire. The outer door mode control switch was found in the normal position. The inner door mode control switch was destroyed by the fire and not found. The rubber seal surrounding the car-to-car door at the aft end
of the coach was partially consumed by the fire, mostly along the upper portion. Both the inner and outer mode control switches of this door were found in the normal position. This door was also found to be in the door pocket with the Lexan window having melted and fallen out of position but still adhering to the door. This precluded the door from being moved to the closed position and is consistent with the door being open when the window melted. The car had two separate air conditioning units, one in the forward equipment bay and one in the rear. The pleated fabric of the particulate filters on both air conditioning units were blackened, consistent with soot being drawn in. The passenger compartment of the lower level was completely consumed by the fire, leaving only small scraps of charred materials. The lavatory area of the lower level was heavily charred and sooted, but the compartments remained intact. The interiors of the lavatories were heavily sooted despite the spring loaded doors being closed.

Figure 3  Left hand side of coach car 34033.

Car 35006

This coach car was the second coach car after the transition sleeper car. The coach had a snack bar in the forward lower level and lavatories in the aft lower level separated by the stairwell and luggage racks. The upper level was a passenger compartment. The rubber seal of the forward car-to-car door was partially consumed by the fire, with more extensive damage on the right side than on the left. The window of the forward car-to-car door had melted and fallen out of position. Both of the door mode control switches were found in the normal position. The car had two separate air conditioning units, one in the forward equipment bay and one in the rear. The pleated fabric of the particulate filters on both air conditioning units were blackened, consistent with soot being drawn in. The snack bar on the lower level had not sustained any fire damage but did have some soot deposition, mostly on the horizontal surfaces of the items found within. The stairwell and luggage rack area were heavily coated with soot, although no materials had been consumed by fire in this area. The hallway leading to the lavatories had some light sooting on the walls. The interior of the lavatories had heavy soot deposition on horizontal surfaces and very light sooting on vertical surfaces consistent with cooled products of combustion entering through the HVAC system. The passenger compartment on the upper level of the coach was heavily sooted throughout. At the forward end of the passenger cabin, the ceiling and luggage rack materials were charred and appeared to have been involved in the fire. This charring extended from the forward end of the passenger compartment to about the 7th row of seats from the front (see figure 4).
Conclusions

Although the cause of the fire was self-evident the investigation did reveal safety issues with the fire protection design and systems of the train cars involved. In this accident, the flammability of the train car interior materials did not appear to have exacerbated the fire spread. The standards for the flammability of materials used in train car interiors [4] are some of the most stringent among the modes overseen by the US Department of Transportation and are second only to the standards required by the Federal Aviation Administration. In this accident, the ignition source was large, and due to the dispersed fuel from the truck, the fire quickly developed. The structural damage to the two cars impacted by the truck and trailer also contributed to the growth and spread of the fire in the first two affected cars. Because the first two of the fire damaged cars sustained severe structural damage upon impact, it is hard to cite the car-to-car doors as the path for the fire spread between them.

However, the fire spread between the second and third cars was not facilitated by structural damage, but solely by fire spread through the car-to-car door. Evidence from the vehicle examination indicated that the doors (and in particular the 2nd car 34033 to 3rd car 35006 car-to-car door) did not remain closed. Additionally, these doors even if closed could not act as a fire barrier due to construction from combustible materials. This condition will allow a fire to move from car to car down the train consist, increasing the passengers’ risk of exposure to the products of combustion during an evacuation. Passengers that may have become incapacitated or injured from impact forces during the accident may not be able to self-evacuate. Preventing the fire and products of combustion from traveling between cars would allow these passengers to survive the accident. For these reasons, the NTSB made the following recommendation to the Federal Railroad Administration:

Require that passenger railcar doors be designed to prevent fire and smoke from traveling between railcars. (R-12-41)

Another issue that was identified was the apparent flow of products of combustion through the HVAC systems in the train cars involved. All of the HVAC filters on all three of the cars exhibited soot. The lavatories of both the 2nd and 3rd fire damaged cars exhibited heavy sooting despite having closed doors. The way the soot was deposited, reminiscent of snow building up on horizontal surfaces but not adhering on vertical surfaces suggested that the soot was introduced through the HVAC vents. This condition can put passengers in compartments far from the fire origin at risk of smoke inhalation, incapacitation, and death. This can be particularly hazardous in the event that impact forces during a
collision trap or otherwise incapacitate passengers in compartments that would not be at risk of exposure to the products of combustion.

**TRUCK-TRACTOR DOUBLE TRAILER MEDIAN CROSSOVER COLLISION WITH MOTORCOACH AND POSTCRASH FIRE IN ORLAND, CALIFORNIA**

**Accident Narrative**

On April 10, 2014, about 5:40 p.m., a 2007 Volvo truck-tractor in combination with two 28-foot trailers, operated by FedEx Freight, Inc. was traveling southbound in the right lane of Interstate 5 (I-5) in Orland, California. In the vicinity of milepost 26, the truck-tractor moved into the left lane, then departed the southbound traffic lanes and entered the 58-foot-wide center median. A motorist traveling southbound on I-5 behind the truck-tractor told investigators that he observed the truck move across the lanes from the right, with no signs of braking or obvious steering input. Another motorist traveling behind the truck-tractor stated that he saw the vehicle’s left turn signal come on, then the truck moved to the left in a motion described as a “continued drift.” The witness did not see any brake lights illuminate. The truck-tractor traveled through the median; entered the northbound lanes of traffic, heading south; and struck a 2013 Nissan Altima four-door passenger car, occupied by the driver and a front seat passenger. The passenger car rotated counterclockwise and departed the highway on the east side. At the same time, a 2014 Setra motorcoach, operated by Silverado Stages, Inc. was traveling northbound on I-5 in the right lane, transporting 42 high school students and 3 adult chaperones. One motorcoach passenger seated a few rows behind the driver recalled seeing the FedEx Freight truck driver “slumped towards the door” with his head down. Following the impact with the passenger car, the truck-tractor collided with the front of the motorcoach. Both the truck-tractor and the motorcoach departed the highway to the east. A postcrash fire ensued (see figure 5). The fire consumed the truck-tractor, significant portions of its trailers, and the motorcoach interior.

**Injuries**

As a result of the crash and subsequent fire, the truck driver, the motorcoach driver, and eight of the 45 motorcoach passengers died. The truck driver sustained a fractured left tibia, was severely burned, and died from asphyxiation due to the inhalation of products of combustion. He was found just outside of his vehicle. The motorcoach driver, who was found near her seat, died from multiple blunt force trauma and was severely burned. Six motorcoach passengers died from asphyxiation due to the inhalation of products of combustion. Three passengers were found inside the motorcoach, two of whom did not exhibit ante mortem (before death) traumatic injuries. Three passengers were found outside the motorcoach and had sustained multiple ante mortem blunt force trauma. The seventh fatally injured passenger, also found outside the motorcoach, died from multiple blunt force trauma. The eighth passenger was found walking away from the motorcoach after the crash and died later that day at the hospital. This passenger had sustained a fractured left arm and burns over 90 percent of his body. Among the fatally injured motorcoach passengers were all three adult chaperones and five high school students. Six of the fatally injured passengers had been seated in rows 1 and 2, one in row 4, and one in row 5. The 10 seriously injured motorcoach passengers sustained both fire-related injuries (inhalation injuries, acute respiratory failure, and second- and third-degree burns) and collision/egress injuries (pulmonary contusions, facial fractures, clavicle and arm fractures, and a spleen laceration). Twenty-seven motorcoach passengers sustained minor injuries, such as lacerations, abrasions, and contusions.

**Vehicle Egress**

The motorcoach had eight windows on each side, four of which were emergency exit windows. The emergency exit windows on the driver side were the second, third, fifth, and seventh and on the passenger side, the second, fifth, sixth, and seventh. Each window was marked and had an instruction sticker. The distance from the base of the emergency exit windows to the ground was 7 feet 1 inch.
Investigators interviewed 29 of the 37 surviving motorcoach passengers regarding their egress from the motorcoach. All stated that they exited the motorcoach using the emergency exit windows; about half responded that they did not know the exit windows existed prior to the crash. Five of the 29 passengers said that they either opened or kicked out the windows. The remaining passengers reported that the thick smoke made it difficult to see anything, including the emergency exit windows, so they followed other passengers to escape. Passengers expressed concerns about exiting the windows due to their height above ground and the difficulty holding the windows open while trying to evacuate. The evacuation process itself caused some passenger injuries.

Two motorists traveling on I-5 northbound provided investigators with video recordings of the motorcoach during the postcrash fire. Video images show the motorcoach engulfed in flames and heavy black smoke, as passengers are seen evacuating and moving away from the fire.

Figure 5  Postcrash fire, photo taken by a bystander.

Vehicle Examination

The on-scene examination included the accident scene, the vehicles involved, and video documentation of portions of the postcrash fire. The full fire investigation factual report can be found in the NTSB’s public docket [5].

Motorcoach Examination

The motorcoach was impacted on the front end by the tractor trailer. This impact tore open the front portion of the motorcoach causing deformation of about the first 6 feet of the vehicle (see figure 6). The motorcoach was substantially destroyed by the fire following the impact. The tire on the steer axle (1st axle) had been consumed by the fire. All combustible materials in the steering axle wheel well had also been consumed by fire including the fiberglass wheel well fairing. The drive axle (2nd axle) had tandem wheels. The rubber tire of the outer wheel had come off the wheel rim. This tire was found lying on the ground beside the motorcoach a few feet away from the drive axle. This tire had some evidence of fire damage but was mostly intact. The inner drive axle tire was partially consumed.
by fire. All combustible materials in the drive axle wheel well were consumed by fire including the fiberglass fairing. The TAG axle (3rd axle) had a single wheel, and the tire was partially consumed by fire. All of the combustible materials in the TAG axle wheel well were consumed by fire with the exception of the rear portion of the fiberglass fairing. The forward portion of this fiberglass fairing was thermally damaged with just the glass fibers remaining in place. The combustion of the tires on the 2nd and 3rd axles left a distinct fire pattern on the exterior of the motorcoach above the wheel wells.

The fuel tank compartment was located just behind the steering axle (this can be observed in figure 6). The exterior panel that encloses the fuel tank compartment was missing. The surface finish on the fuel tank was charred on approximately the lower third of the tank and burned off completely on the upper portion. There was a distinct demarcation between the charred surface finish on the lower portion and the upper portion of the tank that was missing the surface finish. This demarcation began about 18.5 inches from the bottom of the fuel tank on the forward end and 16 inches on the aft end. The fuel tank had a small puncture just a couple inches above this line of demarcation. The fuel tank exhibited bulging consistent with an overpressure event. The filler cap for the fuel tank was missing. There was a witness mark on the overhead structure of the fuel tank compartment just above the filler neck of the fuel tank. This witness mark is consistent with damage that could occur if the filler cap were blown off of the filler neck by pressure inside the tank. The fuel tank was empty at the time of examination. The exterior surfaces of the rear end of the motorcoach had mostly soot from the fire and not charred material. The area of sooting was primarily on the upper portion of the rear above the engine compartment and toward the left side. The rear window glass was missing. Above the broken window, the three lenses of the brake lights were charred. Inside the engine compartment, there was some soot accumulation and limited thermal damage. Combustible materials in the engine compartment had not been consumed by fire. The front end of the motorcoach sustained the most deformation from the impact with the tractor trailer and also the most thermal exposure due to the postcrash fire. The driver’s seat had been displaced outward toward the left side of the motorcoach. The steel pillars that formed the structure of the passenger entrance had been displaced outward and backward toward the right side of the motorcoach. The roof at the front end of the motorcoach had deformed inwards. All of the combustible materials in this forward portion of the motorcoach had been consumed by the fire, including a spare rubber tire. The combustible materials in the interior of the motorcoach were completely consumed by fire. In the forward portion of the vehicle, all of the passenger seats were burned down to bare frames. In the last few rows of seats, limited amounts of charred foam remained attached to the seat frames. In the overhead area of the passenger compartment, all of the structure and linings with the exception of steel components were consumed by the fire. Both of the overhead emergency exit hatches were missing.

Figure 6  Front of motorcoach exhibiting impact damage.
Tractor Trailer Examination

The tractor trailer consisted of a tractor and a double trailer combination unit. The tractor was destroyed by impact forces and the postcrash fire (see figure 7). The collision between the motorcoach and tractor impacted the tractor on the right side. The tractor's frame rail on the right side was displaced inwards at the location of the fuel tank. The fuel tank was not present, and the steel straps that would have attached it to the tractor’s frame had sheared off. The right side fuel tank had a maximum capacity of 150 US gallons. On the left side of the tractor's frame, the steel straps that secure the fuel tank were still present but deformed. The left side fuel tank had a maximum capacity of 100 US gallons. Based on fuel records and average consumption estimated by FedEx Freight party members, the fuel on board the tractor at the time of the accident was about 160 gallons between the two fuel tanks. The tires on the steering axle of the tractor were mostly consumed by fire as were all four tires on the drive axle. A portion of the tractor's fiberglass hood, which had separated from the tractor during impact and was thrown outside the postcrash fire zone, did not reveal any evidence of fire damage that could be attributed to a preimpact fire on the tractor.

Conclusions

The collision between the tractor and motorcoach was almost head on with a shallow angle between their direction of travel. The angle of impact resulted in the rupture of the right side fuel tank of the tractor and the creation of a large opening in the front of the motorcoach. Post incident examination of the tractor suggests that the rupture of the right side fuel tank was a sudden and catastrophic failure, which would have caused a wide dispersal of diesel fuel. The frame rail of the tractor where the fuel tank was mounted had been bent inward toward the centerline of the vehicle and the attachment hardware, which secured the fuel tank to the frame rail had sheared off. This level of damage to the fuel tank’s location on the tractor’s frame suggests that the tank would had been split open on impact. Additionally, a portion of this fuel tank was recovered on scene and exhibited evidence of a catastrophic rupture. The intrusion of the tractor trailer into the front of the motorcoach during the collision caused the entire front of the motorcoach to be ripped open. The dispersal of fuel from the
fuel tank of the tractor coincided with the intrusion of the tractor’s front end into the motorcoach, creating a pathway for the dispersed fuel to enter the forward portion of the motorcoach. The examination of the motorcoach revealed that the two fuel tanks on the coach did not rupture and release their fuel. Thermal damage patterns on the fuel tank exteriors suggest that these tanks retained their integrity and contained their fuel during the fire. The thermal damage patterns on the fuel tank exteriors left what can be described as a “water line” between the liquid level in the tank and the ullage space above. This water line also indicated that the motorcoach was in a slightly (about 7 degree) nose down orientation during the fire. The motorcoach being in a nose down orientation with the front ripped open would have created a chimney effect for the products of combustion being generated at the front of the coach. This chimney effect would be exacerbated by the opening of the emergency escape windows and the eventual burn through of the overhead escape hatches. Smoke was seen coming out at the rear left side of the motorcoach in the video documentation of the post collision fire captured by a witness and the forestry service dashcam while the fire was still at the front. Large clouds of dark smoke seen coming out of the rear left side of the motorcoach coincided with passengers escaping and running across the highway. This video evidence along with statements from surviving passengers confirms that the interior of the motorcoach had quickly filled with smoke (see figure 8). Many passengers said that due to the almost instantaneous smoke filling of the passenger compartment, they could not easily see the locations of the emergency exits. For these reasons, the NTSB made the following recommendations to the National Highway Traffic Safety Administration:

Revise the Federal Motor Vehicle Safety Standards to require that all motorcoaches be equipped with emergency lighting fixtures that are outfitted with a self-contained independent power source. (H-00-1)

Revise the Federal Motor Vehicle Safety Standards to require the use of interior luminescent or exterior retroreflective material or both to mark all emergency exits in all motorcoaches. (H-00-2)

Due to the presence of uncontained diesel fuel and its entry into the forward portion of the motorcoach passenger compartment, the fire that ensued was instantly fully developed and did not go through an incipient and growth stage. The current flammability standard in place for highway vehicle interiors (FMVSS 302) was intended to discriminate materials based on their resistance to ignition sources such as matches, lighters, and smoking materials. These are considered “small” ignition sources and the FMVSS 302 test simulates them using a Bunsen burner. The FMVSS 302 test cannot predict the material’s fire performance when exposed to a larger size ignition source such as the initiating fire in this accident. With the increased crash survivability of modern vehicles, the fire threat is not so much a small interior ignition source but a postcrash fuel-fed fire. In this particular case due to the instantaneous growth of the fire, the ignition resistance of the interior materials would not have had a significant effect on slowing down the fire spread. In this accident, it was not so much the combustion of the interior materials that lead to untenable conditions inside the motorcoach but more so the combustion of the dispersed fuel, tires, and other materials burning at the front of the motorcoach that created the untenable condition. Although the flammability of the interior materials likely did not have a significant role in the survivability of this fire, it is worth noting that the FMVSS 302 standard is outdated and less discriminating than the flammability standards applied in other modes of transportation such as rail and aviation [6]. In addition, the FMVSS 302 standard applies to all highway vehicles regardless of size and passenger capacity. The risk of loss of life increases with passenger capacity as does the time to evacuate. It may be reasonable then to have more stringent standards applied to high occupancy vehicles. For these reasons, the NTSB made the following recommendation to the National Highway Traffic Safety Administration:

Revise Federal Motor Vehicle Safety Standard 302 to adopt the more rigorous performance standards for interior flammability and smoke emissions characteristics already in use throughout the US Department of Transportation for commercial aviation and rail passenger transportation. (H-15-12).
The deformation of the front portion of the motorcoach from the impact and the heat and smoke from the postcrash fire precluded the reasonable use of the passenger entrance for emergency egress. This left the passengers with only the option of using the emergency window exits. In order to operate these windows, the passenger has to be in the standing position to release the latches and climb through the window. This places the passenger’s head in an area potentially filled with smoke because the heated products of combustion will stratify in the upper portion of the passenger compartment. This is counter to the common convention of getting low and crawling to safety in order to avoid inhaling and succumbing to potentially toxic and irritating smoke before reaching safety. If there was a secondary curb height exit from the motorcoach either at the midpoint or rear of the motorcoach, passengers could stay low and avoid the smoke layer above them during egress. For these reasons, the NTSB made the following recommendation to the National Highway Traffic Safety Administration:

Require new motorcoach and bus designs to include a secondary door for use as an additional emergency exit. (H-15-13).

Figure 8  Image from witness video taken within the first 30 seconds after the collision.
REFERENCE LIST


A Case Study on the Use of Reverse FMEA (rFMEA) and the Scientific Method in a Fire Cause Determination

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EXTENDED ABSTRACT

Today the fire investigation community relies heavily on both NFPA®921: Guide for Fire and Explosion Investigations and NFPA® 1033: Standard for Professional Qualifications for Fire Investigator as authoritative standards in the fire investigation profession [1]. Both of these texts, as well as other prominent fire investigation texts like Kirk’s Fire Investigation, stress the use of the Scientific Method for determining the origin and cause of a fire or explosion.

Most fire investigators identify the Scientific Method as the correct and preferred methodology for determining origin and cause during a fire investigation; however, the application and documentation of this methodology vary significantly. Very few formalized tools exist for the practical application of the scientific method in fire investigations and those that do are rarely used or encountered in both published literature and practice [2]. Such a formal tool or procedure should assist investigators in employing critical thinking skills in order to correctly infer specific conclusions from observed data. The tool should also be systematic, intuitive, reliable, and valid. Additionally, its application should serve to document the entire process of hypothesis formulation and testing for future reference.

The authors, in cooperation with a Quality Tools expert, have previously developed and published “reverse Failure Modes and Effects Analysis (rFMEA)” as a methodology to help apply the scientific method for use in fire cause determinations [3]. That paper (Applying Advanced FMEA Methods to Vehicle Fire Cause Determinations) detailed the development and scientific basis of the rFMEA methodology. The present paper, however, will briefly overview the rFMEA process and concepts, specifically concentrating on the practical application of the rFMEA methodology through an actual case study.

We will also demonstrate how the rFMEA methodology meets the objective of assisting investigators in employing critical thinking skills in order to correctly infer specific conclusions from observed data. Furthermore, we discuss its systematic and intuitive nature, its validity and reliability, and its comprehensive documentation of the entire process of hypothesis formulation and testing for future reference.

KEYWORDS: fire investigation, rFMEA, scientific method, fire cause, reverse FMEA, failure analysis, root cause analysis
BACKGROUND and the rFMEA METHODOLOGY

“Failure Analysis and Analytical Tools” (Chapter 22 of NFPA® 921, 2014 Edition) refers to Failure Modes and Effects Analysis as a “technique used to identify basic sources of failure within a system” which “can help identify potential causes of a fire or explosion and can indicate where further analysis could be beneficial.” NFPA® 1033 (2014 Edition) also specifies that “Failure Analysis and Analytical Tools” is one of the sixteen different topics that “the investigator shall have and maintain at a minimum an up-to-date basic knowledge... .”

Today, Failure Modes and Effects Analysis (FMEA) is one of the most widely accepted and commonly used quality tools for design (dFMEA) and process (pFMEA) (adopted particularly early in the automotive industry). Initially introduced in the 1940s by the US military, FMEA quickly gained acceptance in the growing aeronautical and aerospace fields [4] before spreading to the automotive sector and, subsequently, the associated automotive supplier sector. Today FMEA usage is gaining in the Medical, Information Technology, and Renewable Energy sectors as well. Since Ford Motor Company’s early introduction of FMEA to the American automotive industry, this ever evolving tool has become a powerful technique for helping designers recognize and evaluate potential product failure modes early in the design and manufacturing processes, eliminating or reducing potential failures and their associated effects [5]. More importantly, FMEA has primarily been a design tool for improving products and processes. Currently, the Fire Protection Engineering community also utilizes FMEA techniques as the basis for qualitative Fire Risk Analysis [6].

More specifically, FMEA is a predictive engineering tool that fosters a deeper understanding of the potential causes and effects of failures in a design. FMEA also assists in the definition and prediction of the possible effects of a potential failure while still in the design phase. In this way, failure modes can be mitigated or designed out of a product before they are ever produced [7]. Risk information produced by FMEA’s assignment of severity, occurrence, and detection criteria can guide and prioritize the design process. Finally, all of this FMEA information can then be tabulated for future reference and updated as new information becomes available. As such, it is a repository for product and process design and performance knowledge, acting as a foundation for continuous product and process improvement. Most products, components, and processes involved in the modern automotive industry today have evolved, in design and development, using variations of this methodology.

FMEA is primarily a predictive design process. In contrast, determining the cause of a failure that results in a fire is a reactive investigation process. Because of this, an investigative process such as a Root Cause Analysis is more appropriate for fire cause determination. Root Cause Analysis (RCA) methodology applies to a wide variety of quality tools that have historically been used to analyze failures. RCA seeks to arrive at a cause at the “root” of a failure. The root cause is the first, the base, the initiating cause, starting an undesired sequence of events. If eliminated, the root cause has no opportunity to start a causal sequence of cascading events. The root cause answers the “why” question asked in common RCA techniques such as 8-Disciplines Problem Solving, Fault Tree Analysis, Ishikawa Diagrams, Pareto Analysis, and the 5-Why methodology (favored by Toyota Motor Corporation and originally developed by Sakichi Toyoda). Every one of these different techniques presumes that for every effect, there was a prior-occurring cause [7]; hence, the commonly used phrase: “cause and effect.” More recently, this relationship has been further refined for use in the FMEA process as “cause, failure, and effect.” This refinement recognizes that, from a more practical and rational standpoint, every cause and effect in an RCA is also associated with an intervening failure.

| Cause | Failure | Effect |

*Figure 1 Cause, failure, and effect sequence*
In this paper, as in general quality tool terminology, “failure” is defined as the inability to perform an intended function. This definition ensures the proper application of this methodology in order to fully determine and analyze the significant causes, failures, and effects in the critical failure process. Thus a “failure” in this analysis is not necessarily a failure defined in a legal sense, a sense that incorporates the ideas of risk, responsibility, and liability.

RCA techniques strive to determine how every effect can be traced back to its original or root cause. By applying FMEA sequencing to RCA, we can connect every effect, such as an effect observed during a vehicle fire investigation, to a failure, and connect every failure to a cause. The linear and sequential nature of these events means that every cause also has a pre-occurring cause (of the next order), until the root cause can be determined (to the order of detail required for the circumstances of the particular analysis). From a practical application approach, FMEA and RCA can be thought of as chronologically mirrored opposites. FMEA looks forward to predict how a design will perform or potentially fail and to determine the risks associated with those failures. On the other hand, RCA looks back to see what failures may have occurred during the design, manufacturing, or maintenance processes [8]. Because these sequences are mirror opposites, we can therefore reverse the FMEA methodology to arrive at a root cause methodology, designated as reverse FMEA (rFMEA). This chronological life cycle of a vehicle system or component – through its initial design, a fire event, and the causal investigation – can be symbolically expressed as follows:

![Chronology of a Product Fire Failure](image)

The application of the “reverse FMEA” technique also allows an investigator to reference the original design and process FMEAs to determine if a possible fire cause was evaluated as an original design or process potential failure mode. Any causal information that was originally not considered or improperly assigned severity, occurrence, and/or detection criteria, can then be updated in previous FMEAs, providing real world feedback to the FMEA process for continuous product improvement at the design and process level.

A failure analysis fire investigation begins with the systematic establishment of an area or point of fire origin through traditional fire investigation tools such as witness information, fire patterns, and fire dynamics [9] (Arc Mapping is not a valid tool for determining a vehicle fire’s origin) [10]. Next, the investigator determines the cause of the fire. This process requires discovering and understanding the sequence of events and factors in the product’s design, manufacture, assembly, usage, maintenance, repair, and/or environmental conditions that combined in unexpected ways to produce the fire. Fire cause determination involves identifying the first fuel ignited, the ignition source, and the circumstances that resulted in the fire [11]. After determining an area or point of origin, the “rFMEA” approach provides a framework which sorts out the complexities of each product system and their interactions in a systematic and well documented process that drives towards a scientific determination of root cause. This method is especially useful in situations where multiple potential causes may be theorized from the determined effects and subsequent failures, complicating the root cause determination. As demonstrated in the following case study, the potential causes of the fire were narrowed down to failures in three separate electrical circuits added to the vehicle. rFMEA analysis helped determine which of the three potential circuits was involved in the cause of the fire. Though...
the entirety of the cause determination process used an rFMEA analysis framework, the case study highlights these final three electrical circuits for demonstrative purposes.

**rFMEA AND THE SCIENTIFIC METHOD**

Using the Scientific Method is required for the determination a fire’s cause in the investigation community, as referenced in both NFPA\® 921 (Guide for Fire & Explosion Investigations) and NFPA\® 1033 (Standard for Professional Qualifications for Fire Investigator). These two publications define the Scientific Method as the following 7-Step process: 1) recognize the need, 2) define the problem, 3) collect the data, 4) analyze the data, 5) develop a causal hypothesis, 6) test this hypothesis, 7) arrive at final hypothesis.

In vehicle fire cause analysis, Steps 1 and 2 are defined generally in the assignment of the fire investigation, “a vehicle fire occurred and we need to understand how and why the fire happened” and “we can proceed by conducting a fire origin and cause investigation” [12]. Therefore, we can primarily focus on Steps 3 through 7: the collection and analysis of the data, and the development and testing of all “reasonably possible” hypotheses. Eventually “impossible” hypotheses will be eliminated, moving the investigation toward the determination of all valid hypotheses and hopefully one probable fire cause.

Using the reversed “Effects - Failure - Cause” model described above, we will now discuss how to apply the sequence to Steps 3-7. “rFMEA’s” first step determines the observable effects of the fire in the previously determined area or point of origin. This corresponds with Step 3, the collection of data. The process of collecting data on a fire-damaged vehicle fire consists of the notation of all the observable effects of the fire within the area or point of origin. Typical observable effects include shorted and beaded wires, ruptured hoses, broken turbocharger shafts, transmission fluid missing, cracked or broken components, etc. This information is then listed in the first column of the rFMEA form in Figure 2.

As noted in the introduction, every effect is associated with a failure. Therefore, the fourth step is the analysis of the observable effects and the consideration of the potential failures that could lead to the specific effect (one or more possible failures may exist for each observable effect). These effects are listed in the second column. Keep in mind that during this stage failures essentially constitute a lack of function. The function of an electrical power circuit’s wiring is to convey power to an electrical component. That function could be disrupted by a short circuit related to a lack or insufficiency of insulation isolating the conductor. Related factors might include the type and thickness of the wire insulation, how it is clipped to prevent chaffing, or the environmental appropriateness of the insulating material. This emphasizes the importance of an investigator’s familiarity with the design function of the components under evaluation in order to ensure an effective analysis. This step in the process corresponds to Step 4 of the scientific method: analyzing the data.

Next, the analyst must note that each failure had a cause and should consider each cause to be the immediate and pre-occurring reason for the failure. As mentioned earlier, failures can have more than one potential cause. Because of this, all potential causes must be listed with each failure to be analyzed later in order to determine its corresponding potential causes. By following this format, the methodology considers every cause that may have occurred. The cause and alternate potential causes are listed in the third column of the form in Figure 2. The next step in the methodology seeks to determine the cause of the cause (2\(^{nd}\) order cause), then the cause of the cause of the cause (3\(^{rd}\) order cause), and so on until the most probable root cause is found or when the analysis no longer makes sense. The causal sequences that terminate because they no longer make sense are the hypotheses that fail. The most probable root cause should become apparent after no more than the 5\(^{th}\) order cause, according to the “5-Whats” methodology. To quote Taiichi Ohno, father of the Toyota Production System, the 5-Why method is “the basis of Toyota’s scientific approach… by repeating why five times, the nature of the problem as well as its solution becomes clear” [13]. In NFPA\® 921 terminology, every hypothesis is developed and evaluated, i.e. tested. Alternatively, this “Effect -
Failure - Cause, Cause of Cause, etc.” logic path can be thought of as a tool to test your causal hypothesis. The hypotheses that fail will have to stop, and the hypotheses that do not fail will eventually identify the most probable root cause. This step in the procedure correlates to Steps 5-7 of the scientific method: developing and testing the hypothesis and arriving at the final hypothesis. Using NFPA® 921 terminology, the single final hypothesis remaining can be identified as the most probable root cause, provided only one hypothesis survives the testing process (it is possible for more than one hypothesis to survive the analysis). This information should be added to columns 4-7 of the form. Notably, this methodology meticulously documents all considered hypotheses for future reference.

Another significant aspect of the rFMEA methodology is that of hierarchical alignment. Consider it as a tool which helps to determine if events are linear succeeded causes or preceding events. This subject, though important, expands beyond the scope of this brief introduction.

**CASE STUDY:**

**VEHICLE DESCRIPTION**

The vehicle studied here is a 21-passenger bus built on a 16,000 pound gross vehicle weight rating (GVWR) cut-away van chassis. The cut-away van chassis was manufactured by a major original equipment manufacturer (OEM), while the bus body was manufactured and installed by a separate final stage manufacturer, i.e., up-fitter. At the time of the fire, the vehicle had just over 100,000 miles on the odometer and had been in service for approximately six years. The bus body featured a large passenger main entry bi-fold door on the front right side of the bus and a wheelchair lift on the rear right side. An additional battery box was mounted between the front entry door and the wheelchair lift underneath the frame. This battery box contained one additional battery and was wired in parallel with the standard chassis battery, which was located in the front right side of the engine compartment. The extra battery helped to power the chair lift. Both batteries were last replaced approximately two months prior to the fire. The vehicle’s main alternator was upsized to 200 ampere (A) rated capacity to account for the larger electrical loads and to provide sufficient current charge to both batteries.

All of the chassis electrical loads remained in the original OEM fuse boxes. The chassis manufacturer also equipped the vehicle with “customer pass thru circuits” that were available both at the main OEM fuse box, in the OEM auxiliary fuse box, and at the “B” pillar to provide convenient connection of accessories without the need to drill through the cowl and into the engine compartment to access battery power. All of the electrical system fuses for the bus body were in an additional separate fuse box installed by the up-fitter, located on the front right side of the bus interior mounted directly to the floor and just forward of the main entry door. This additional body fuse box was equipped with a battery feed terminal for convenient access to battery power, as well as an unused pre-wired, fused radio connection points to facilitate the installation of aftermarket radios.

Shortly after the bus was purchased, a 2-way radio (meant for dispatcher/driver communication) was installed by a third party, as in other exemplar buses in the fleet. This same third party was also responsible for the continued maintenance of these radios. The radio was designed to require three electrical connections; main electrical power to the radio, an ignition power sensing electrical connection, and a ground wire. All three circuits were installed with 12-gauge wiring. The radio product information specified the power circuit should have been fused at 20A and the ignition power sensing circuit at 4A. The only other electrical aftermarket modification was the installation of a windshield mounted video event recorder. This video camera was installed with three 16-gauge wire electrical connections; one fused with a 3A fuse supplying power to the camera, one circuit for ground, and one circuit fused with a 3A fuse for ignition power sensing. Ignition power sensing allowed the camera to come on only when the vehicle is running.

Inspection of exemplar units with similar 2-way radio installations by the same third party showed the radios were directly wired into the up-fitter floor mounted fuse box using fuse taps. A fuse tap is a nonconventional electrical connection of either a bare wire inserted into one of the terminals of a fuse block, or alternatively a metallic terminal that is inserted into an existing fuse. Neither is an
appropriate connection as the fuse blocks are not designed to accommodate them, and their use may overstress the fuse block terminal. This bus fleet previously experienced intermittent electrical problems caused by the use of fuse taps. Additionally, a type of fuse tap is available in the automotive aftermarket that replaces a fuse directly in the fuse panel and converts one slot in the fuse box into two slots, although these are often not recommended and, according to the manufacturer of the fuse taps, should never be used for circuits exceeding 10A. Typical 2-way radios draw just under 20A.

CIRCUMSTANCES

Three days prior to the fire incident, the bus was taken out of service and the batteries were disconnected after the driver reported having electrical problems with the instrument panel lights upon returning to the transit facility. The bus was parked in the garage with the key in the “off” position, which was then stored in the main office. The next day, the bus would not start and was connected to a battery charger. The keys were returned to the main office. The battery charger was still connected to the bus at the time of the fire two days later. According to the surveillance video, the bus began to smoke from the top of the passenger door, overnight on the third day after it was parked. Approximately 20 to 30 minutes later, visible flames appeared from the top of the right side passenger door.

DETERMINATION OF ORIGIN

The complete details of the fire origin process in this investigation are outside the scope of this paper. However, it is appropriate to mention that a high degree of confidence rests in the origin of this fire as the incident was captured on a surveillance video. The video shows smoke beginning to emanate from the vehicle and then shows flames coming out of the top of the main passenger entry door. This video evidence was also consistent with the fire patterns remaining on the vehicle after the fire. These patterns were distinctive and well defined as the vehicle was parked in a building equipped with a sprinkler system that prevented the fire from spreading extensively. The fire patterns observed, the fire dynamics and materials involved, and the fuel loads available are all consistent with an origin area of the front right side bus body, just inside and forward of the main passenger entry door on the floor and upward. This is also the location of an electrical fuse panel installed by an up-fitter that supplies power to the bus body. The 2-way radio and event video recorder were wired into the bus in this spot as well.

DETERMINATION OF CAUSE

Because this paper seeks to illustrate the use of the rFMEA process, we will not discuss the initial fire cause analysis prior to the exclusion of all potential fire causes other than electrical causes within the determined area of fire origin. The complete analysis followed the rFMEA process framework but is not included in order to focus on the limited demonstrative examination of the final fire cause analysis.

Three primary “observable electrical effects” were found and identified in the previously determined area of fire origin. These three observable effects generated sixteen potential causal hypotheses which, through the rFMEA process, were narrowed down to just one probable cause. These three observable effects are as follows:

The first (1) was a short section of a 12-gauge electrical circuit added to a maxi fuse block which ended in a metal globule. This maxi fuse connection is normally unused (based on an inspection of similar exemplar buses) and is connected directly to the battery at all times, even with the ignition off. This circuit was connected to the maxi fuse block using a flag connector crimped to a 12-gauge wire. There were only 5¼ inches of wire found remaining with the flag connector and a metal globule at the end of the wire. The metal globule is a possible indication of beading from an electrical short circuit or may also simply be caused by the ambient melting of the wire. The analysis and determination of the globule’s creation will proceed out of the rFMEA process later. There was no evidence found that
this circuit was fused and it was determined to be the main power circuit to the 2-way radio due to its direct connection to battery power.

The second effect (2) was another short section of a 12-gauge electrical circuit added to a mini fuse block that also ended in a metal globule. This circuit was added using a fuse tap to the power side of the mini fuse block at a connection that normally fuses the dome light in the bus (based on a fuse panel diagram from the up-fitter). This circuit is only powered when the ignition key is on. No evidence suggests that this circuit was fused. Since this circuit is powered only when the ignition is on, this was determined to be the 4A ignition power signal connection for the 2-way radio. There were 8¾ inches of wire found remaining with the fuse tap. The wire ended in a metal globule in what could, at this point in the analysis, be interpreted as the aforementioned melting or beading.

The third (3) was a section of a 16-gauge electrical circuit connected directly to the positive battery terminal of the fuse panel. This electrical junction is always powered. This circuit was protected by a 3A in-line fuse and was determined to be the electrical power for a front-facing digital event camera, based on the sizes of the wire and fuse. The end of this wire also ended in a metal globule, similar to the other two wires.

All three electrical circuits with observable effects ended in separate metal globules, which could be interpreted as either melting or beading, depending on the skill of the investigator and the extent and depth of the analysis. Through use of the rFMEA methodology, further interpretation or analysis of the metal globules at the end of the circuits was determined, in this case, to be unnecessary for identifying the root cause. This process of elimination provided a more reliable root cause determination that did not depend on conflicting current controversial theories of the analysis of such globules.

We also know that there were no other electrical modifications made to this vehicle. We can therefore determine that the two 12-gauge electrical circuits ending in melted globules were electrical power circuits to the 2-way radio, as noted above. This is based on the fact that the wires were: a) the correct gauge, b) larger than 16-gauge wires used by the video event camera, and c) connected to the fuse panel like the radio installations in other exemplar vehicles inspected. The ground circuits for both the 2-way radio and video camera were unremarkable and later determined to be uninvolved.

rFMEA ANALYSIS

The rFMEA analysis process starts by identifying each of these observable effects on a spreadsheet. The first effect described above is the beaded 12-gauge wire connected to the fuse box with a flag connector, listed in the table in Figure 3 below. The next rFMEA analysis step determines the failure associated with this effect. All three significant observable effects involved electrical power wires that ended in a metal globule. As noted previously, a “failure” is generally defined as the inability to perform an intended function. Thus in this analysis, the failure associated with each of the three electrical power circuits could be described as the wire’s “Inability to Convey Electrical Power.”

The rFMEA analysis then proceeds with the determination of potential causes for each failure. Without the need for further study of the metal globules at the end of each wire, each possible cause for the similar failures can be listed for each wire, as shown in Figure 3. Potential causes for each failure were determined to be: an electrical short circuit, ambient melting of the wire and high resistance connections – all which could produce a metal globule at the end of an unconnected electrical power wire. All of these cause options are considered as a potential first order causes.

Next, we continue the cause-failure-effect model and consider all of the different reasons why the circuit could have shorted, experienced ambient melting, or experienced a high resistance connection. As illustrated in Figure 3, a short circuit occurs when the insulation on a wire is worn through and allows a connection to ground. Insulation can wear through due to either relative motion allowing for the insulation to chafe, or because the wire was pinched during installation. In all of these cases, this
circuit may or may not have been fused. Even if the circuit was fused, it is possible for the short circuit to occur on the power side of (wire prior to) the fuse, negating the protection afforded by the fuse. If this wire melted due to the ambient temperatures in the fire instead of shorting, then that must logically have been an effect of the fire and not a cause, allowing us to cease this analysis. If we consider the possibility that the radio was off at the time of the fire, a high resistance connection could not have been a cause since no current was being drawn through the circuit. When this matrix of options is expanded, we end up with seven hypotheses for why this wire show signs of beading or melting. The three hypotheses associated with melting and a high resistance connection can be ruled out. The four remaining hypotheses all support an electrical short circuit. The only question that cannot be answered is whether the root cause was an “un-fused” installation of this circuit, or if the short circuit occurred because the fuse was installed too far away from the source of power. Responsibility in both cases falls on the third party installer/maintainer.

Figure 3  rFMEA First Observable Effect

The second observable effect was a 12-gauge wire ending in a globule installed with a fuse tap to a circuit that is only electrically powered when the key is in either the “run” or “accessory” position. Therefore, the analysis is identical to the one above and generated seven more hypotheses. However, the potential cause analysis stops because the key was in the “off” position and the circuit had no power. This effect then cannot be linked to a probable cause of the fire as shown in Figure 4.

Figure 4  rFMEA Second Observable Effect

The third observable effect becomes an abbreviated version of the analysis presented above and only generated two more potential hypotheses. The logical potential causal sequence stops since the circuit was properly fused for this application as shown in Figure 5.

Figure 5  rFMEA Third Observable Effect
The rFMEA analyses for each of the three individual effects are combined in Figure 6 providing a concise documentation of the scientific method analysis leading to a probable root cause for this fire that satisfies the requirements and purposes previously noted for both NFPA®921 and NFPA®1033.

CONCLUSIONS

The fire cause investigation conclusion derived from this analysis is the probable cause of this fire was a short circuit in the main electrical power feed to the 2-way radio. This short circuit occurred either because the circuit was not fused or because the short circuit occurred prior to the possible fuse installation location. A short circuit in the un-fused radio power circuit would overheat the wire, causing the wire insulation to burn. This indicates the wire insulation was the first fuel ignited. Once the wire insulation starts to burn, the fire spreads to the other plastic components in the fuse box, including the fuse box cover, and then to other parts of the bus body, consistent with the fire dynamics and video witness information.

We reached this conclusion after evaluating sixteen different possible hypotheses derived from just three observable effects. Tabulating these different hypotheses in cause-failure-effect order helps ensure that all reasonable options for each failure are considered. This tabulation also assists the investigator in their attempt to easily identify which of the possible causes are not consistent with the circumstances of the fire and the possible cause(s) that are consistent with the fire evidence. Any hypotheses that are consistent with the fire evidence are the final hypotheses, or the determined root cause(s), depending on your preferred terminology. Any new information or data that is collected at a later time can also be easily added to the tabulation to see if the results change.

The goals for this rFMEA analysis process were to help correctly infer specific conclusions from the observed data, to be both systematic and easy to understand, and to be reliable and valid. It should
also document the entire process from gathering data to hypothesis formulation and hypothesis testing. All of these objectives have been met while strictly adhering to the Scientific Method as described by NFPA® 921. This example is very simple and straightforward and the same conclusions could have been derived without the use of the rFMEA methodology; however, this example was chosen specifically because it is simple, allowing for an emphasis on the process instead of getting lost in the details of a more complex investigation.

**REFERENCE LIST**

Detecting Leaks in Commercial Vehicles Fueled by Natural Gas & Propane

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PURPOSE

The purpose of this paper is to provide an overview of a two-hour on-line training developed for commercial vehicle inspectors to detect leaks in natural gas and propane heavy trucks and buses.

BACKGROUND

The fuel system is one out of fourteen safety-critical parts of commercial vehicle; serious defects in a safety-critical part are defined by the North American Standard (NAS) Out-Of-Service (OOS) criteria [1]. The NAS OOS criteria for fuel system calls for a commercial vehicle to be placed Out-Of-Service if it is leaking fuel.

The Federal Motor Carrier Safety Administration (FMCSA) is the United States Department of Transportation (USDOT) agency that regulates the safety of operating and maintaining commercial vehicles (heavy-duty trucks and buses). FMCSA published a final report [2] in 2013 on updates suggested in the Federal Motor Carrier Safety Regulations (FMCSRs) to address natural gas commercial vehicles, NAS inspection procedures, and NAS OOS Criteria. FMCSA has also developed a training for inspectors to detect leaks in natural gas and propane commercial vehicles in response to a request from the Commercial Vehicle Safety Alliance (CVSA). CVSA is an international not-for-profit organization comprised of local, state, provincial, territorial, and federal motor carrier safety officials and industry representatives from the United States, Canada, and Mexico. CVSA develops NAS inspection procedures and develops the NAS OOS Criteria. {Note: The nationwide commercial vehicle inspector and officer workforce consists of 13,195 state, provincial, and municipal personnel and 533 federal personnel (mostly stationed along the United States southern border) and [3]}. In June 2013, CVSA expressed a need to FMCSA to help train inspectors to detect leaks in natural gas and propane commercial vehicles.

OBJECTIVES OF THE TRAINING

- How inspection of fuel system fits into the NAS commercial motor vehicle inspection procedures
- How to identify a commercial motor vehicle with a fuel system using
  - Compressed Natural Gas (CNG)
  - Liquefied natural Gas (LNG)
  - Liquefied Petroleum Gas (LPG) (also known as propane)
- Most important fuel properties for leak detection
- Overview of a typical natural gas or propane fuel system
- Most likely places in a natural gas or propane fuel system for a leak
- Detecting and confirming leaks
- Human sensory clues
- Soap bubble test
- Combustible gas detector
- What to do if a vehicle has a fuel leak
HOW INSPECTION OF FUEL SYSTEM FITS INTO THE NAS COMMERCIAL MOTOR VEHICLE INSPECTION PROCEDURES

The NAS commercial motor vehicle inspection procedures are for trucks with conventional diesel fuel systems, in which steps 16 and 26 of the 37-step procedure, involve examining the saddle fuel tanks. FMCSA will develop new NAS commercial vehicle inspection procedures for accommodating trucks with natural gas fuel systems when the National Highway Traffic Safety Administration revises Federal Motor Vehicle Safety Standard No. 304, “Compressed Natural Gas Fuel Container Integrity” [4]. In the meantime, the detection of leaks described in this paper represents an ad hoc, stand-alone procedure that is deployed at the inspector’s discretion.

HOW TO IDENTIFY A COMMERCIAL MOTOR VEHICLE WITH A FUEL SYSTEM USING COMPRESSED NATURAL GAS, LIQUEFIED NATURAL GAS, OR LIQUEFIED PETROLEUM GAS

The inspector should look for a diamond-shaped label on the lower rear of a vehicle. To identify the vehicle as a natural gas vehicle, the inspector should look for a diamond-shaped label with the white letters “CNG” or “LNG” on a blue background. To identify a LPG vehicle, the inspector should look for a diamond label with the word “PROPANE” in silver or white on a black background. These labels are NOT required by FMCSA, but by the National Fire Protection Association (NFPA) 52 [5] and NFPA 58 [6], both of which are voluntary codes that have been adopted by most states in the United States of America.

MOST IMPORTANT FUEL PROPERTIES FOR LEAK DETECTION

The five most important physical properties useful for detecting leaks of fuels are the state of matter, color, odor, lower flammable limit, and leak profile. The state of matter refers to what form the fuel is: gaseous, liquid, or solid. Diesel fuel is a liquid. CNG is a gas compressed at 24,821 kPa, LNG is a liquid cryogen at -162° C, and LPG is a pressurized liquid (generally around 1,724 kPa). A pressurized liquid can be either a liquid and/or a gas depending on its temperature and pressure. Color is self-explanatory. Diesel fuel is black so it can be easily detected, but CNG, LNG, and LPG are colorless. Odor is also self-explanatory. Diesel fuel has a petroleum odor. However, CNG, LNG, and LPG are naturally odorless. An odorant, such as methyl mercaptan, is added to CNG and LPG to intentionally make them perceptible to the nose at low concentrations. LNG cannot be odorized.

The lower flammable limit is the lowest (also leanest) concentration of a fuel mixed with air that will burn. Generally, this is expressed in percent (on a volume of fuel to volume of air basis). For example, the lower flammable limit for diesel fuel is 0.6%. The lower flammable limit for natural gas (regardless of whether CNG or LNG) is 5%, and for LPG is 2%. The lower flammable limit is used in conjunction with a combustible gas detector (described later).

The leak profile of a fuel refers to the pattern in which a fuel leaks. Diesel fuel leaks from a container or a pipe by dropping on to the lowest level, such as the ground. CNG fuel leaks rise because the specific gravity of natural gas is 0.6 to 0.7, which is lighter than air. LNG fuel leaks tend to first drop and form puddles on the lowest level; however, as the temperature of the leaking LNG warms up to the ambient temperature, it forms a vapor cloud, then rises and dissipates. LPG leaks tend to fall to the lowest level and stay at the lowest level because propane is heavier than air with a specific gravity of 1.5 to 2.0.
OVERVIEW OF A TYPICAL NATURAL GAS OR PROPANE FUEL SYSTEM

CNG, LNG, and LPG fuel systems have the following in common: one or more fuel tanks (with a pressure relief valve or pressure relief device), fuel fill portal, fuel pump, fuel filter, pressure regulator, fuel lines (high and low pressure), and either a fuel vaporizer (for LNG) or an evaporator (for LPG).

MOST LIKELY PLACES IN A NATURAL GAS OR PROPANE FUEL SYSTEM FOR A LEAK

The most likely places in a natural gas or propane fuel system for a leak are as follows: joints or elbows in solid (rigid) fuel lines, tank shut-off valves, connection to the engine, fuel fill portal, pressure regulator, and fuel filter.

DETECTING AND CONFIRMING LEAKS

The most frequently used method for detecting leaks is human sensory clues; these include sensory clues from a sulfurous smell of the odorant (e.g., methyl mercaptan), a hissing sound, a visible puddle on ground and/or vapor cloud. Suspected leaks must be confirmed with a soap bubble test or a combustible gas detector (described later). Vehicles in which suspected leaks cannot be confirmed must be issued a repair order.

SOAP BUBBLE TEST

For the soap bubble test, the inspector should spray a non-corrosive detergent solution onto suspected leak locations and observe the sprayed areas for persistent bubbling, which indicates a leak. The inspector should NEVER check for leaks using a lit match or lighter.

COMBUSTIBLE GAS DETECTOR

The other method of confirming a leak is to use a combustible gas detector. Detectors range in costs from 50 USD to 1000 USD. Detectors can be used to check for leaks where there are no obvious conventional leak clues, especially in closed compartments, such as the driver’s cab, engine, fuel storage, and cargo compartment. Because detectors are quantitative, they can be used to pinpoint the source of a leak and to determine if a threshold is exceeded.

The recommended OOS threshold is 25% of the lower flammable limit (LFL) because of this threshold is generally accepted for activating alarms at an indoor facility [7]. LPG has LFL of 2%, thus, the OOS threshold should be 25% x 2% = 0.5% (or 5,000 ppm) for a propane. Natural gas has LFL of 5%, thus, threshold should be 25% x 5% = 1.25% (or 12,500 ppm). To simplify matters, CVSA decided to make the OOS threshold the more conservative of the two, that is, the OOS threshold is 5,000 ppm.

In using a combustible gas detector, an inspector needs to remember to apply the leak profile of the fuel of the vehicle being inspected: because natural gas vapors rise, the detector should be used to check the top of a compartment where vapors could accumulate. Because LPG vapors fall, the detector should be used to check the bottom of a compartment where vapors could accumulate.

WHAT TO DO IF A VEHICLE HAS A FUEL LEAK

If the vehicle has been confirmed to have a fuel leak, the inspector should issue an OOS order for the vehicle. For a combination vehicle, only the power unit (tractor) is placed OOS -- not the trailer(s) and not the driver. Also, a vehicle placed OOS for a fuel leak must NOT be operated, moved or towed unless de-fueled. If it is necessary to move the vehicle with a fuel leak because it is blocking traffic, the vehicle may be moved a short distance to a safer location, but it must NOT be stored.
indoors unless the facility is approved for storage of natural gas or LPG vehicles by the authority having jurisdiction.

**LINK TO THE 2-HOUR, ON-LINE TRAINING**


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Fire Protection of Military Ground Vehicles and their Crews

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ABSTRACT

Fire protection, both active and passive, is a significant part of the design, development and deployment of modern ground vehicles. Fire hazards are mitigated by separating the vehicle occupants from the most flammable materials, e.g., fuel and ammunition, as much as practical. Additionally, all US military vehicles carry handheld fire extinguishers, and many tactical and all combat vehicles have automatic fire protection systems that protect the crew, engine, and in some cases, external components such as fuel tanks and wheels, from potentially catastrophic combat events involving fire. Explosion protection of the crew and passengers in military vehicles is a unique application with unique requirements that must balance suppression actions with safety limits. This paper presents an overview of the fire threat, how the occupants of military ground vehicles are protected from thermal injury, and how risks to rolling assets are mitigated.

KEYWORDS: military vehicles, explosion protection, automatic fire protection

INTRODUCTION

When combustible fluids and flammable materials are stored in close proximity to potential ignition sources, as they inevitably are in ground vehicles, fires are a real and present danger. Modern military vehicles use diesel or JP8 fuels which are, due to the relatively high flash point temperature, much less of a fire hazard than gasoline, the fuel used in earlier vehicles. Nevertheless, all fuels, hydraulic fluids and most lubricants are flammable and the fires in modern military vehicles continue to cause significant vehicle damage and casualties.

'Peacetime' fires in military ground vehicles are similar to commercial vehicle fires:

- Fuel, hydraulic fluid, or lubricating oil component failures can lead to leakage of flammable liquids that are ignited by contact with hot surfaces and/or sparks.
- Electrical component failures or corrosion can lead to overheated circuits that ignite wire insulation or oily contaminants and other combustible materials.
- Overheated brake components and trapped road debris can cause fires in wheel wells. (Wheel well fires can also occur if a vehicle operates too long on ‘run-flats’ designed to offer temporary support when the main tires are deflated.)

As is the case with industrial heavy-duty vehicles, hand-held fire extinguishers (HFEs) are deployed on all military vehicles. If used properly, HFEs are generally effective in suppressing and extinguishing small, slow-growth peacetime fires, but cannot be relied on to protect against fast-growing, explosive fires that can occur in combat. Protection against combat fires requires a fast and automatic system.
The first automatic fire extinguishing systems (AFES) deployed by the US Army in ground vehicles were developed for the Abrams, Bradley Fighting Vehicles (BFV), Field Artillery Ammunition Support Vehicles (FAASV), and later the Stryker family of vehicles. More recently, a variety of similar fire protection systems have been deployed on mine-resistant ambush-protected (MRAP) and up-armored high-mobility multipurpose wheeled (UAH) vehicles.

The threats the AFES are designed to protect against are combat-initiated fires caused by a penetration of the vehicle where fuel or other petroleum, oil, or lubricant (POL) is involved. For example, a penetrating threat enters the vehicle and impacts a POL reservoir resulting in a spray of flammable fluid that is ignited by residual threat elements causing an explosion (technically a fast deflagration). During Operation Desert Storm, the Abrams and BFV AFES were reported to be effective in protecting vehicle crews from such combat-initiated POL-fueled fires [1].

How is a combat fire best described? The Abrams specification for the AFES fire sensor gives one example when it requires (see Table I in [2]) that the AFES fire sensor respond with an alarm signal when exposed to a ‘fireball’ explosion, defined as follows:

“The radiation level equal to or equivalent of that produced by a fuel oil fire ball explosion which grows from 1.0 inch or less to 4.0 feet or larger in diameter instantaneously at 5 feet and less from the sensor.”

Subsequent tests on the BFV and other platforms confirmed this definition of a combat explosion as a reasonable one, and it is currently routinely simulated by a fuel-spray fire during AFES verification tests [3]. In these tests, the “fireball generator” (FBG) is oriented to simulate a threat penetration deemed realistic by the platform program management team and/or independent evaluator. Current live-fire test methodologies are routinely reviewed to insure that they reflect realistic scenarios to adequately evaluate systems intended to protect against the newer threats. For example, simulations of field-expedient Molotov cocktails (FEM) have recently been included in validation testing of tactical vehicle fire protection.

As a result of the new threats encountered during the wars in Iraq and Afghanistan that pose significant risk of fires, vehicles have added passive fire protection systems such as powder panels or blankets that enclose and protect fuel tanks in addition to an AFES. Some vehicles also use active fire extinguishing systems to protect their external fuel tanks and/or the tires. Self-sealing fuel tanks have been developed and are also deployed on some vehicles.

High-level attention to ‘lessons learned’ relevant to fire protection is not new. In 1986 an Army blue ribbon panel focused on vehicle fires and recommended particular attention to defining realistic operational requirements and ensuring that fire protection systems are functional when needed. The 1995 Design of Combat Vehicles for Fire Survivability Handbook (MIL-HDK-684) details lessons learned at that time. Topics covered include: bilge design, engine type, design and location of fuel cells and fuel lines, space heaters, and routing of hydraulic lines [4].

The Middle Eastern conflicts led, among other things, to a much wider range of vehicles and thus fire protection systems. The associated proliferation of part numbers has greatly complicated logistics and made vehicle down-time more likely. Hence effort has been applied to both reducing the number of part numbers, and streamlining the support processes.

Advancements in vehicle development, especially those associated with the power train and fuel, may create relatively new fire hazards that require somewhat unique mitigation means. Recent collaborative efforts to understand emerging electric vehicle fire hazards (e.g., those associated with Li-ion battery technologies) and develop applicable safety standards are notable examples. Nevertheless, casualties attributed to fires in military vehicles occur, and vehicles continue to be lost to fire. Clearly the need for vehicle fire research, in all applications, continues.
MILITARY GROUND VEHICLE FIRE EVENTS

How big is the fire problem? In a study of tank fires during the conflict in Vietnam, it was found that the casualty rate was, on average, roughly three times higher in incidents that involved fire, and almost half of all tank casualties occurred in fire incidents [5]. Although the best current data available [6] don't offer a direct comparison to earlier data, according to it, approximately 1.5% of attacks on US Army vehicles in Iraq and Afghanistan resulted in fires. A total of 220 casualties were attributed to combat fire in the period from 2002 through 2012. These casualties, comprised of wounded in action (WIA) and killed in action (KIA), are summarized in Table 1.

Table 1  Summary of US combat casualties attributed to fire.

<table>
<thead>
<tr>
<th>Theater</th>
<th>Attacks</th>
<th>Fires</th>
<th>WIA</th>
<th>KIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEF*</td>
<td>17,970</td>
<td>240</td>
<td>62</td>
<td>25</td>
</tr>
<tr>
<td>OIF/OND**</td>
<td>25,828</td>
<td>401</td>
<td>56</td>
<td>77</td>
</tr>
<tr>
<td>Total</td>
<td>43,798</td>
<td>641</td>
<td>118</td>
<td>102</td>
</tr>
</tbody>
</table>

* Operation Enduring Freedom, 01 Jan 2007 - 31 Dec 2012  

Additionally, dozens of accidental/peacetime vehicle fires occur annually and some result in casualties: 33 injuries and 7 fatalities were a result of 35 accidental/peacetime fires that occurred in the 2002 through 2012 period.

FIRE PROTECTION SYSTEM DESIGN

No safety system can be effective unless it is designed with a well-defined threat, or set of threats, in mind. Fire protection systems are no exception [4]. Hence, the first step in designing a fire protection system to protect the crew in a ground vehicle from combat threats is to understand the nature of the threat, and how it may cause a catastrophic fire.

In addition to being effective against fire threats, the fire protection systems must meet the general environmental and operational vehicle requirements. After these requirements are defined for a target vehicle, qualified components must be integrated into systems on the vehicle and then the system’s performance validated. The key design and development steps are:

1. Define requirements  
2. Component verification  
3. Integration of qualified components onto the vehicle  
4. Validation of system performance

Requirements

The detailed requirements for each platform vary. Tracked and wheeled vehicles have different operating and mission profiles; however, there are many similarities, both generally and specifically related to fire protection. A recent specification supporting the BFV modernization program is fairly comprehensive [7].

General

The general requirements for sub-systems aboard a vehicle apply to the fire protection systems. These requirements include:

- Human engineering factors/ergonomics  
- Safe-use criteria
• Mechanical and thermal abuse
• EMI and EMC immunity and effects
• Nuclear survivability
• Space and weight claims
• Integration compatibility
• Reliability
• Commonality
• Maintainability
• Availability and cost

**Unique to Fire Protection**

The general requirements for sub-systems aboard a vehicle do not usually include requirements that are essential for adequate fire protection performance. Fire protection specific requirements generally include:

• Fire suppression capability and performance
• Appropriate suppression agent(s)
• Adequate and safe agent concentration levels
• Manual release: mechanical and/or electrical
• Backup power (independent, not co-located with, vehicle power)
• Automatic fuel and/or air flow shutoff(s)

**TYPES OF FIRE PROTECTION SYSTEMS**

**Crew Compartment AFES**

The AFES that protects the crew compartment is unique in that this military application is the only one that offers explosion protection to an occupied area. In this application the fire protection system must extinguish a POL-fueled fire before the crew is incapacitated. Thus there is a tradeoff between what is most effective at suppressing an explosion and what is safe for occupants (per human injury criteria). Table 2 summarizes the requirements that are generally most significant in designing and verifying the crew compartment AFES [8-14].

**Engine AFES**

Current Army vehicles typically require that the engine AFES “…protect the engine compartment against petroleum, hydraulic fluid and other slow growth fires, as well as explosive hydrocarbon fires from threat weapon penetrations or explosions with an automatic first shot and a delayed or manually activated second shot to extinguish the fire without reflash….” The time within which the AFES must perform varies. For example, some applications require that the engine AFES act within 10 seconds of detection, and others require extinguishment without reflash within 10 seconds of fire detection or within 60 seconds of ignition, whichever occurs first. [15]

**Tire Fire Suppression**

Several wheeled vehicles have tire fire suppression systems installed. The design goals of the tire fire protection system are to [16]:

• Fully extinguish the fires within 25 seconds of ignition
• Minimize flame spread to external vehicle stowage
• Require no occupant action for extinguisher function
• Disperse extinguishant only in the area in and around the fire
• Present no hazard to personnel around the vehicle
• Require no scheduled maintenance for at least four years
• Provide manual backup operation capability

**Fuel Tank Fire Protection**

Besides automatic systems, protection from fuel tank fires is generally provided by passive means such as armor, air gaps and, recently using dry chemical ‘powder pack’ jackets. Dry chemical powder packs protect the fuel tank by dispersing fire extinguishing agent when they are penetrated. Some vehicles have recently implemented so-called ‘crashworthy bladders’ to minimize leakage in the event of the failure of the fuel tank enclosure due to a non-penetrating event, e.g., an underbody blast that does not breach the floor. Self-sealing coatings and liners have also been investigated and recently deployed on several platforms. In some vehicles the fuel tanks are mounted externally in ways that minimize the risk of a catastrophic fuel fire inside the vehicle (e.g., with an air gap between the fuel tank and the vehicle hull).

**Ammunition Fire Protection**

Currently, while possibly mitigating secondary fires, active extinguishing systems are not effective against ammunition fires directly. Ammunition fires are best addressed via passive approaches including storing the ammunition separately from the crew, in a compartment with blow-off panels that, when a fire occurs, relieves pressure build-up to reduce the risk to the crew and vehicle [17].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Suppression</td>
<td>Extinguish all flames without reflash</td>
</tr>
<tr>
<td>Skin Burns(^a)</td>
<td>Less than second degree burns ((&lt;2400^{\circ}\text{F-s over 10 sec or heat flux &lt; 3.9 cal/cm}^2))</td>
</tr>
<tr>
<td>Toxic Gases(^a)</td>
<td>Acid Gases (HF + HBr + 2∙CO(_2)) &lt; 746 ppm-min (5 min dose) (\text{Other toxic gases (e.g., CO}_2, \text{CO, NO}_x, \text{HCN) are also measured})</td>
</tr>
<tr>
<td>Overpressure(^b)</td>
<td>Lung damage &lt;11.6 psi; Ear damage ≤ 4 psi</td>
</tr>
<tr>
<td>Oxygen(^b)</td>
<td>Levels at breathing locations of at least 16%</td>
</tr>
<tr>
<td>Agent(^c)</td>
<td>Concentration within occupational safety limits</td>
</tr>
<tr>
<td>Discharge Impulse Noise(^d)</td>
<td>No hearing protection limit: &lt;140 dBP (\text{Single hearing protection limit: &lt;165 dBP})</td>
</tr>
<tr>
<td>Discharge Forces(^e,f)</td>
<td>Not to exceed 8 g and &lt;20 psi at 5 inches</td>
</tr>
<tr>
<td>Fragmentation(^g,h)</td>
<td>Ejected non-agent particles &lt;300 micrometers (\text{Non-Shatterable Cylinders (NONSHAT)})</td>
</tr>
</tbody>
</table>

(a) Per reference [8].
(b) Per reference [9].
(c) See reference [10].
(e) Extrapolated from reference [8].
(f) See reference [12].
(g) Section 3.4.1.3 in reference [13].
(h) Section 3.3.9 in reference [14].
Component Verification

Qualification

As a basic requirement, components used in fire protection systems need to be qualified to the relevant portions of the vehicle specification, including the general, e.g., environmental, and AFES-specific requirements, e.g., fire extinguishing performance.

Highly Accelerated Life Tests (HALT)

Above and beyond qualification, as a means to reduce risks of failure once integrated onto a vehicle, it is desired that components be subjected to highly accelerated life tests (HALT) early in the design process, before they are integrated onto a vehicle. The HALT results should clearly identify:

- The margin by which the component exceeds the minimum qualification levels
- Weak links in the component design

The HALT environment typically subjects the component being tested to simultaneous mechanical and thermal stresses. The environmental excursions are expected to exceed those required by the specification, generally to the point where the component fails. This approach allows the component detailed design to be improved efficiently [18].

System Integration

Different vehicle platforms have varying POL reservoir locations, capacities, geometries, layout and stowage. The AFES must be integrated on each vehicle so that it is optimized for that vehicle and its mission requirements. The number and types of fire sensors and extinguishers, and their associated mounting and accessory locations, required to protect a given part of the vehicle, e.g., the crew compartment, will depend on the application-specific details of each vehicle platform. Similarly the location and configuration of the AFES control electronics will be vehicle specific.

For any vehicle sub-system to be effective, its components must be integrated correctly. This means that fire protection components must be installed so that they survive events that they are designed to protect against, and can operate without interfering with other vehicle systems and operations.

Fire sensors must be located so that they can detect fires without preventing the crew from performing their duties, and without inadvertently becoming convenient steps or storage devices, e.g., helmet hangers. Similarly, the extinguisher discharge nozzle(s) must be located so that, in normal operations, the agent distribution pattern will be effective without endangering the occupants or being obstructed by stowage or the occupants themselves. Control interfaces, for example the manual discharge switch(es) and/or pull handle(s), must be located so that they are accessible in the event of a catastrophic event. The electrical harnesses must be routed so that they are likely to survive events that may result in the need for the AFES to operate. Similarly, the independent backup power supply must be located so that it can survive a threat that damages the vehicle’s primary power system.

These considerations, along with those associated with crew safety, must be considered for all vehicle configurations. The effects of normal crew positions, air flow, environmental extremes, and minimum and maximum stowage must also be addressed.

Once the (often iterative) integration process is complete, the resultant system should have a well-defined list of components, mounting locations, as well as the associated weight and space claims.
System Verification

A fire protection system must be well integrated in order to work effectively and safely, regardless of how proven and qualified the components are. The system must address the hazards identified for the target platform, as well as be able to survive the environments expected for the vehicle missions. The performance of the integrated AFES must be verified by a multi-step process described below.

Agent Distribution

A well designed fire protection system produces agent concentration levels throughout the protected volume that are simultaneously fast enough to suppress an explosion before it causes crew incapacitation and safe for occupants in their normal positions for at least five minutes, generally providing sufficient time to vent the vehicle, for egress, or for rescue [8].

While achieving sufficient agent concentration for fire suppression within a few seconds is adequate for most peace-time fires, such as in a machinery space, explosion protection requires much faster delivery and concentration development. To ensure that the AFES will provide adequate explosion protection for the crew compartment, concentration levels must be measured at multiple points in the compartment with a fast sampling rate: at least every 12 milliseconds. The ‘rule-of-thumb,’ developed empirically during many years of testing, is that in order to have confidence that an AFES will be effective in a live-fire test, it must produce a fire suppression agent concentration in the critical areas of protection of at least the minimum design concentration (e.g., 8.7% for HFC-227ea per [10]) within about 300 milliseconds after the start of a fast fire, followed by a more uniform, inerting concentration.

Safety

As described in the ‘Crew Compartment AFES’ section, fire protection systems on combat vehicles must extinguish fires before the fire incapacitates the crew, without injuring them. Thus there is often a tradeoff between what is most effective at suppressing an explosive fire and human injury criteria. For example, the AFES must limit discharge fragments, impulse noise and force, and agent concentrations to safe levels.

Fire Extinguishing Performance

Ultimately fire protection systems must prevent the occupants in combat vehicles from being incapacitated due to fire, thus giving them opportunity to continue their mission or escape. The systems must be effective against combat and peacetime fires. Verifying that these systems are effective requires tests using realistic fire threats [19]. Typically, non-ballistic tests, usually fuel-spray fires, are used to verify system performance prior to tests against relevant ballistic threats as required by Congress [20]. Instrumentation for these tests includes [8, 19]:

- High-speed video inside the protected area
- Normal video in the protected area, and the vehicle exterior
- Blast overpressure
- Temperature
- Heat flux
- Gases including $O_2$, CO, $CO_2$, NO, $NO_2$, HCN, HF, HBr, $COF_2$, and the suppression agent

Fuel-Spray Fire Tests

It is faster and less expensive to test using a fuel spray fire than it is to test with a ballistic threat. In the 1990s the US Army Tank-Automotive Research, Development and Engineering Center (TARDEC) and Aberdeen Test Center (ATC) developed a fuel spray fixture that simulated the post-penetration flame propagation, blast overpressure, and temperatures of an actual ballistic penetration
This ‘fireball generator’ (FBG) rapidly sprays pre-heated fuel into a test chamber that includes an ignition source resulting in a fast-growth fire that typically fills the compartment in less than a second. The FBG can be used to simulate almost any shot line through the crew or engine compartments of ground vehicles.

**Ballistic fire tests**

A Congressional mandate [20] requires that vehicle capabilities critical to the safety of the crew and their mission be tested using actual expected and relevant threats. In these tests an independent evaluator is responsible to review and approve the test plan and assess the results.

**Vehicle Trials**

Although qualification of components is a necessary step in the development process, it alone is not sufficient to guarantee success in the application. A protection system can only be effective if it can survive on the vehicle during operations. Trials on an operating vehicle are a test of the integrated system(s) and its robustness. Therefore, after components are qualified, they need to be assembled into an integrated system on a vehicle and subjected to operational trials. The trials generally involve vehicle operational extremes on- and off-road. Any subsequent vehicle changes need to consider the effect on the fire protection systems and may require re-testing.

**CURRENT CHALLENGES**

**Environmental issues**

Since the mid-1990s the US Army has strove to use more environmentally friendly materials wherever possible. The fire suppression agent used in the original ground vehicle fire protection systems was Halon 1301 (CF3Br) which is an ozone-depleting substance, and finding Halon replacement suppression agents that are both environmentally friendly and offer adequate performance has been a major area of effort. The result was that Halon 1301 used to protect machinery (unoccupied) spaces was replaced with a variety of agents including dry chemical and hydrofluorocarbons (HFC). New platforms use a blend of heptafluoropropane (an HFC) and dry chemical to protect the crew compartments. However, a "drop-in replacement" (i.e., something that fits the same space claim as what is deployed now) for the crew fire protection systems in legacy vehicles (i.e., ones deployed before 2000) has not been identified, so halon continues to be used in this limited set of applications. Additionally, the non-ozone depleting HFC replacement agents identified a decade ago have significant global warming potential (GWP) so a second generation replacement program may be required. Initial investigations that compared low- or no-GWP fire suppression agents with current ones showed some promise for future development but offer nothing close to a drop-in replacement [21]. The 2015 Paris Climate Change Agreement [22] has resulted in a renewed effort to identify fire suppression agents with low- or no-GWP.

**Broader range of protection**

**Overmatching threats**

During the recent asymmetric Middle East conflicts, opportunities for improving the level of protection in legacy and newer vehicles emerged. Fire protection is needed for crews who are trapped in vehicles that may be on their side or upside down, perhaps in large external fires. Technologies being explored include faster detection to allow the compartment to be filled with agent before the fire grows significantly, orientation insensitive extinguishers, and egress protection [23, 24]. TARDEC has also worked with the US Marine Corps (USMC) to develop two-stage suppression systems where the second stage applies an aqueous cooling agent for a relatively long duration [25].
**Non-POL fires**

Fires that pose significant risk to the crew and vehicle are not always fueled by petroleum oil and lubricants (POLs). Fires fueled by non-POLs may have significantly different optical emissions, possibly challenging fire sensors designed to detect POL fires, and such fires may not be suppressed by extinguishing agents that are effective against POL fires.

Fires and explosions that involve ammunition are beyond the capabilities of current fire protection technologies and will probably continue to be so. Passive, compartmentalization methods have been shown to be effective in minimizing the damage due to ammunition fires [17].

The hazards associated with lithium-ion (Li-ion) batteries, which unlike conventional lead-acid batteries use combustible electrolytes, in a combat environment are relatively unknown. However, the fire risks that have emerged in the commercial ground and air vehicle applications of large Li-ion batteries are an indication that the combat risks may be significant and need to be better understood. The US Army is conducting tests aimed at identifying specific risks posed by large Li-ion batteries and developing mitigation strategies [26].

**Size and weight**

During the recent Middle East conflicts, it became necessary to add fire protection systems to tactical vehicles. Since most tactical vehicles are smaller and lighter than combat vehicles, size and weight of the systems is relatively more important. As part of larger efforts, the US Army has been on the lookout for smaller and lighter technologies [21, 27].

**Life-cycle costs**

Adding fire protection systems to tactical vehicles has resulted in a more than tenfold increase in fielded fire protection systems compared to when only combat vehicles included that protection. In addition to the larger quantity of systems, a proliferation of part numbers occurred – there are few common parts between seemingly similar systems. It turns out that product reliability and maintenance procedures that were acceptable for the smaller population of combat systems are not sustainable for the much larger combined population of combat and tactical systems. The fire protection component that demands the most attention in this arena is the extinguisher. Consequently, the TARDEC fire protection team initiated multiple contracts with fire protection systems suppliers that were aimed at developing extinguishers that are more reliable and cost less during their service life [27]. Concurrently, the Army logistics team has developed a Fire Suppression Sustainment Strategy to more cost-effectively manage and support currently fielded fire extinguishing systems with field refill stations [28]. One consequence of fielding refill stations is that single-use extinguishers are no longer a practical option [29].

**SUMMARY**

Fire protection is an active area of focus during the design, development and deployment phases for all modern ground vehicles. US military vehicles employ a variety of fire protection systems, both passive and active. Automatic fire protection systems protect the engine, crew, and in some cases the wheels, from potentially catastrophic fires. Additionally, vehicle designs often mitigate fire hazards by separating the vehicle occupants from the most flammable materials, e.g., fuel and ammunition, as much as practical. No approach is perfect and the challenge is dynamic; operational experiences must be used to define requirements to better protect military ground vehicle crews from injury due to fire. Finally, it is important to understand the life-cycle costs of technologies before they are deployed.
REFERENCES

7. “Upgrades on Bradley M2A3 automatic fire extinguishing system (AFES),” Solicitation Number W56HZV-09-C-0644, 18 March 2011.
13. “VALVE AND CYLINDER ASSEMBLIES, HALON 1301,” MIL-DTL-62547D,
17. See section 4-6.2.2.2 “Ammunition Magazines for the M1 and M1A1 MBTs” in MIL-HDBK-684 (ref. 4)
20. Title 10 › Subtitle A › Part IV › Chapter 141 › § 2399 - Operational test and evaluation of defense acquisition programs.


**DEFINITIONS/ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AFES</td>
<td>Automatic fire extinguishing system</td>
</tr>
<tr>
<td>ATC</td>
<td>Aberdeen Test Center</td>
</tr>
<tr>
<td>BFV</td>
<td>Bradley Fighting Vehicle</td>
</tr>
<tr>
<td>FAASV</td>
<td>Field Artillery Ammunition Support Vehicle</td>
</tr>
<tr>
<td>FBG</td>
<td>Fireball Generator</td>
</tr>
<tr>
<td>FEM</td>
<td>Field-Expedient Molotov Cocktail</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HALT</td>
<td>Highly Accelerated Life Test</td>
</tr>
<tr>
<td>HFE</td>
<td>Hand-Held Fire Extinguisher</td>
</tr>
<tr>
<td>HFC</td>
<td>Hydrofluorocarbon</td>
</tr>
<tr>
<td>MRAP</td>
<td>Mine-Resistant Ambush Protected</td>
</tr>
<tr>
<td>POL</td>
<td>Petroleum oil and lubricant</td>
</tr>
<tr>
<td>TARDEC</td>
<td>Tank-Automotive Research, Development and Engineering Center</td>
</tr>
<tr>
<td>UAH</td>
<td>Up-Armored High-Mobility Multipurpose Wheeled Vehicle</td>
</tr>
<tr>
<td>USMC</td>
<td>US Marine Corps</td>
</tr>
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</table>

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New Test Method for Fire Detectors in the Engine Compartment of Heavy Vehicles

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ABSTRACT

Engine compartments of heavy vehicles are, in general, spaces where detecting fires with inexpensive and simple fire detection systems is arduous. High temperatures, high airflows, complicated geometries, large amounts of soil, dust and pollutants, and the wide range of surface temperatures, complicate the operation of all types of detectors. More advanced fire detection systems will, on the other hand, have durability issues caused by vibration, shocks, temperature variations and corrosion. SP Fire Research has developed a new test method to evaluate the detection performance as well as the durability of detection systems installed in engine compartments of heavy vehicles. A standardised test method would mean that only efficient detection systems are placed in service. SP Fire Research has worked over two years analysing engine compartments and fire scenarios from a fire detection point of view, including pre-tests of different fire detection systems. This article gives an overview of the challenges of heavy vehicle engine compartments with respect to fire detection and an outline of the new test method.

KEYWORDS: fire detection systems, heavy vehicles, buses, engine compartments, SP Method 5320

INTRODUCTION

Fires in heavy vehicles are unfortunately common around the world and annually involve substantial public cost. For instance, fires in mines are predominantly caused by service vehicles, drilling rigs and loaders [1, 2], and statistical data indicates that nearly one percent of the buses registered in northern Europe will suffer an incident related to fire during a one year period [3-5]. The consequences of a vehicle fire depend on the type of fire, type of vehicle and the surrounding environment. Underground mines, tunnels and cities are environments where a vehicle fire may have dramatic consequences and for buses the fires will be a substantial threat to human lives due to the high number of persons situated inside the vehicle. Early fire detection can be vital for evacuation and will also enable extinguishment at an early stage, both defeating a threat to life and reducing costs.

Statistical data indicate that approximately two thirds of vehicle fires start in the engine compartment [6-8]. Furthermore, the number of fires in the engine compartment may increase in the future due to stricter regulations on noise and emission levels which result in higher operational temperatures. High temperatures, high airflows, complicated geometries, large amounts of soil, dust, and pollutants, and the wide range of surface temperatures typically occurring during normal operation of the vehicle, complicate the operation of all types of fire detectors in engine compartments. A standardized test method for fire detection systems in engine compartments of heavy vehicles would mean that only efficient detection systems are placed in service.

SP Fire Research has put significant work into improving fire safety of heavy vehicles, with focus on buses, the last 10 years. In 2010 a project was initiated with the purpose to develop a test method for evaluating automatic fire suppression systems meant for bus engine compartments [9]. The test method, SP Method 4912, was launched in 2013 and has gained a strong international sympathy [10,
Parts of the method have been implemented in the European legislation for buses, through UNECE Regulation 107 [12]. Swedish as well as foreign bus manufacturers have expressed a desire of the standard to include a test method for fire detection systems, as an elaborate standard would create competitive neutrality keeping a high safety level. Given the obvious importance of including fire detection systems SP initiated a project for this purpose in 2013. The main objective was to develop a test method for evaluating fire detection systems meant for engine compartments of heavy vehicles, including but not limited to buses, which now has resulted in SP Method 5320. This method will complement SP Method 4912 to increase fire safety of buses and other heavy vehicles.

In addition to a new test method for fire detection in engine compartments, the project has also included a study [13] to provide guidelines for fire detection in toilet compartments, in driver’s sleeping compartments and in other separate compartments on buses and coaches. A broad reference group, including vehicle manufacturers, vehicle operators, transport authorities, insurance companies and fire detection system suppliers, has been part of the project and has given valuable feedback on research results as well as on the new test method, SP Method 5320.

NEED FOR A NEW STANDARD

There are good prospects to extinguish and limit the consequences of vehicle fires if they are detected at an early stage. However, vehicle fires are most often detected by the driver, by passengers or by other people passing by, even though fire detection systems may be installed [4, 14]. Full scale experiments have shown that if a large fire breaks out in the engine compartment of a bus there might be only three minutes available for evacuation [3, 15]. Experiments and fire investigations have also shown that the time available, after the fire is detected by the driver, can be insufficient for evacuation of a complete bus [15, 16].

For buses today, the European legislation, through UNECE Regulation 107 [12], requires that the driver is provided with an acoustic and a visual signal in case of an excess temperature in the rear engine compartment. Existing automotive requirements, like Regulation 107, have no performance requirements for fire detection systems. At best, general approval standards for fire detection systems are used, such as EN 54, ISO 7240, FM 3210, UL 268, etc. These product approval standards are comprehensive, but they are developed for fire detection in buildings and do not cover the extreme environmental conditions encountered in the engine compartments of heavy vehicles [17]. The new FM standard related to off-road vehicles, “FM 5970 Heavy Duty Mobile Equipment Protection Systems”, include fire detection systems in the durability tests, but refer to general product approval standards for testing detection performance. Early detection will be a challenge in engine compartments of heavy vehicles and detection systems installed should be tested specifically for that application. A study [18] previously performed by SP shows how the complex geometries and airflow in an engine compartment may affect fire detector performance. Through CFD-simulations it is shown that heat detectors are highly affected by ventilation and location and likely would not detect a fire unless its plume impinges directly on the sensor. This has also been confirmed in full scale testing [19, 20].

USE OF A NEW STANDARD

A new standard and test method for fire detection in engine compartments will improve the safety level of heavy vehicles. The requirements should guarantee that the system has an acceptable performance and durability level, but the test results should also point out strengths and weaknesses of the system with respect to different fire scenarios, vehicle types and driving conditions. With the possibility to compare different fire detection systems, the vehicle operator or manufacturer can choose a better system if a higher safety level is desired. This will also motivate fire detection system manufacturers to improve the detectors and get better test results.

It is important that the tests not wrongly favour or disqualify a certain detection technology or system configuration. The tests should therefore represent a realistic fire challenge and be conducted in a test
setup which is similar to what the system would experience when installed in a heavy vehicle engine compartment. With that in mind, it is also important that the test setup and test procedure is repeatable and reproducible. This will enable a technology-neutral comparison of different fire detection systems to be available for vehicle manufacturers and operators.

ENGINE COMPARTMENT CHALLENGES

In order to develop a new test method for fire detection in heavy vehicle engine compartments, the challenges of fire detection for this application must be analysed. Below, some observations that were found to impact fire detection systems are presented. The observations are followed by the approach used in the new test method to evaluate fire detectors with respect to these challenges.

Geometry and obstructions

The geometry and volume of engine compartments of different heavy vehicles vary a lot. There could be large cubic compartments of 10 m³, with almost no components more than 1.5 m above the compartment floor, to small compartments of 1 m³, 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 either almost empty or fitted with extra equipment.

Fire tests performed have showed that obstructions play an important role for flame detectors. Small obstructions that do not seem to screen much of the radiation could affect the shape and characteristics of flames and prevent or delay detection. Moreover, complex geometries complicate the installation of all types of detectors. It could be difficult to determine where heat and smoke accumulate and in general there is need for several detectors to cover the complete engine compartment.

Common fire detector approval standards do not consider complex geometries and obstructions, which are important to include for an evaluation of detector performance. In SP Method 5320 a mock-up of a typical engine compartment, developed for evaluation of fire suppression systems in SP Method 4912, is used for fire detection performance tests. Examination and testing have shown that the mock-up is suitable also for evaluation of fire detection systems. Moreover, the use of the same setup for both detection and suppression systems joins the two methods, creating a complete method for testing of active fire protection systems. The performance tests for fire detection systems include requirements on coverage of the engine compartment, which means that several fires around the compartment shall be detected, as well as evaluation of response times for two different fire scenarios.

The engine compartment mock-up is well developed and established, and represents a balanced mixture of different types of obstructions. However, as mentioned before, engine compartments of different heavy vehicles vary a lot. It is therefore important with a complementary risk assessment of the real engine compartment before installation of the detection system. The risk assessment should provide answers both on how to install the system to cover all possible fire risks and on how to scale the system based on the results from the engine compartment mock-up tests.

Figure 1 and Figure 2 illustrate the engine compartment mock-up used in the test method. Pool fire tray positions used in the compartment coverage tests are visualised and are spread throughout the compartment. A fixed fire detection system installation shall detect each of these fires to ensure proper dimensioning of the system.
Figure 1  Sketch of the engine compartment mock-up with pool fire trays positions, seen from the front side. The cylinder outside the left wall is the fan generating airflow through the compartment.

Figure 2  Sketch of the engine compartment mock-up with pool fire trays positions, seen from the rear side.

Airflow

Engine compartments are usually well ventilated by the engine fan. However, some vehicles have separate fan and engine compartments, or a partly separated compartment using a screen to direct the flow of air downwards below the vehicle. Depending on the driving conditions the ventilation rate in the engine compartment can also range from a very small to a very high airflow.

The study [14] mentioned previously, shows the impact that ventilation in an engine compartment may have on heat and smoke detector performance. Especially heat detectors would likely not detect a fire in high airflow unless its plume impinges directly on the sensor.
In the tests in the engine compartment mock-up some scenarios will include forced airflow generated by an external fan. An airflow rate of 3 m$^3$/s simulates that the engine is running with high speed and an airflow rate of 1.5 m$^3$/s simulates that the engine is idling or running with low speed. No forced airflow simulates that the engine is turned off or that the vehicle has separate fan and engine compartments.

**High temperatures**

Due to stricter regulations on noise and emission levels the engine compartment temperatures have risen. Generally the air temperature reaches between 80-100 °C, however, in special applications with hard working vehicles it could easily reach 120 °C, and close to turbocharger and manifold the temperatures may reach over 150 °C. The diagram in Figure 3 shows the air temperature about 20 cm above manifold and turbocharger of an underground mine truck during a 24 hour cycle. The peaks reaching 190 °C are very short in time, but the measurements show that steady temperatures of about 140 °C can be expected close to hot surfaces in this environment. Measurements further away from hot surfaces showed maximum temperatures between 80-120 °C, depending on different measurement points. [21]

![Air temperature measurements about 20 cm above manifold and turbocharger of an underground mine truck.](image)

The high temperatures will affect both performance and durability of fire detectors. Heat detectors, which are the most common detector type in engine compartments of heavy vehicles, will have a very high fixed temperature alarm threshold level due to the high temperatures normally encountered in the engine compartments. The high alarm threshold level in combination with a complex ventilated space make heat detectors insensitive to small fires. The coverage test in SP Method 5320 will ensure that all types of fire detection systems can cover the complete engine compartment and detect fires before they grow too large. Without this type of test it is likely that vehicle fires in the future still most often will be detected by the driver or persons nearby the vehicle.

Included in the test method is also a high temperature aging test. This will ensure that polymers used as parts of the fire detection system will not unduly degrade, altering the performance of the detector over time.

**Dirt, dust and pollutants**

Dirt, dust and pollutants are a normal part of an engine compartment and cause problems especially for smoke detectors. New vehicles often have more concealed and tighter engine compartments due to noise requirements, which could result in slightly cleaner compartments. The amount of dirt is therefore depending on the type of vehicle, but also highly depending on the surrounding environment. In the project, tests have been performed with e.g. a city bus (Figure 4), where
measurements of particle concentrations and particle distribution and evaluation of smoke detectors were conducted during different driving conditions [21]. Historically smoke detectors have been regarded as unsuitable for engine compartments of heavy vehicles, but now they have been started to be used [22]. However, the risk of false alarms must be considered and supervision of the sensing chamber and filters is recommended. Supervision of flame detectors is also important to avoid obscuration of the detector lens by dust and dirt.

Figure 4  City bus driving in gravel area.

The new test method is neutral for different detection technologies and any combination of heat, flame and smoke/gas sensors can be tested. However, there will be reliability requirements for smoke/gas and flame detectors with regard to contamination.

Fire detection systems will be required to hold IP-classification for protection against high pressure water jets normally used for cleaning of engine compartments. Figure 5 gives an indication of the dirt accumulation in a truck engine compartment after just a few days in an underground mine. Although not all vehicles operate in such an extreme environment it is common with cleaning of engine compartments once a week, with the exposure of sensitive components for high pressure water jets.

Figure 5  Engine compartment of a truck operating in an underground mine.
Hot surfaces
The presence of hot surfaces in the engine compartment is an important fire safety challenge. The external surface temperature of turbo chargers and exhaust system can be in excess of 600 °C during certain conditions. In addition of being an ignition source, hot surfaces are also a challenge with regard to false alarms. The heat radiation may activate both heat and flame detectors, and oil and grease on the exhaust system may give rise to false alarm of smoke detection systems. For the latter there is however a narrow line between false alarm and early warning. Flame detectors normally manage to differentiate between a flame and a hot surface internally, while heat detectors must be positioned far enough away from potential hot surfaces.

The test method includes evaluation of heat detectors with regard to the minimum distance to a hot surface where the detector can be positioned without initiating an alarm. Figure 6 shows a possible setup with a gas burner heating a metal surface and with the detector exposed for the heat radiation from the surface at the opposite side. The diagram in Figure 7 shows the temperature of a thermocouple soldered on to the centre of the hot surface at the detector side (not the side where the gas burner is positioned). This test will rate the systems with regard to the detector’s resistance to hot surfaces, but the distances cannot be transferred directly to installation guidelines. If a detector is installed close to a hot surface the detector may degrade over time and be more prone to false alarm. Surrounding temperature is also most often higher in an engine compartment than during tests.

![Figure 6](image1)
*Figure 6  Hot surface test setup. A gas burner is heating a metal surface and the detector is exposed for heat radiation from the surface at the opposite side.*

![Figure 7](image2)
*Figure 7  Surface temperature at the centre (hottest spot) of the metal surface in Figure 6 at the detector side when heated by a gas burner.*
Vibration, shock, corrosion and temperature variations
The durability of any components in heavy vehicle engine compartments is a challenge due to severe vibrations and shocks, corrosion by liquids, salt and pollutants, and large temperature variations. The test method refers to recognized international standards used in the vehicle industry to test the durability of fire detection systems. Standards referred to are ISO 16750 and ISO 21207.

Vibrations are always present as long as the vehicle engine is on, induced both by the engine itself and through driving. The vibration test in the test method focus on random vibrations, with alternate frequencies and amplitudes, simulating rough-road driving and is combined with a temperature cycle to stress the system. Shocks occur more irregularly and can be induced by driving over a curb stone or a hole, driving off-road, or other impacts on the vehicle body and frame. Fire detection systems intended for off-road vehicles will, according to the new method, be subjected to an additional shock test, and FM 5970 has been used as basis for this additional shock tests.

Vehicles driving on salted winter roads or by the seacoast will be subjected to salt and water with high risk of corrosion. Corrosion may also occur due to atmospheric pollutants or due to exposure of liquids used in the engine compartment, such as engine oil, antifreeze fluid or water containing vehicle washing chemicals. The new test method evaluates the system response on accelerated exposures to all of these chemicals.

Fire scenarios
Many different fire scenarios including different types of fuels, different ignition sources and different growing rates can be realised in an engine compartment. However, from a fire detection point of view there are especially two different scenarios that fire detection systems can respond differently to. These are smouldering fires or slow growing fires, which typically are electrical fires, and large flaming fires, which typically are spray fires or pool fires due to a fluid or gas leakage. Some detection systems will respond quickly on one of the scenarios but have problems with the other. E.g. flame detectors can detect a large flaming fire in less than one second but have problems with slow growing fires and smoke detectors can detect a smouldering fire before there are any flames, but are slower than flame detectors for large fires.

The new test method will evaluate the response time of fire detectors for both slow growing fires and large flaming fires in the engine compartment mock-up. Figure 8 shows the flames from a gas burner inside the engine compartment mock-up. This fire is possible to slowly ramp up from a tiny flame to a large fire of 100 kW and even more, being both repeatable end reproducible.

Figure 8 Fire inside the engine compartment mock-up.
CONCLUSIONS

To ensure early detection and durability of the systems, there is need for a new test method for fire detectors installed in heavy vehicle engine compartments. Many of the challenges encountered in engine compartments are not specifically tested for in conventional approval standards for fire detection systems. These challenges are, for example, complex geometries cluttered with obstructions, high airflows, high temperatures and hot surfaces, dirt and dust, vibrations and shocks, and corrosion. Without a test method developed for this application it is likely that the driver and other persons will continue to be the ones detecting the fires. It is fairly common that fire detectors installed in engine compartments today are not positioned close enough to the fires to be the first to respond.

SP Method 5320 comprises system coverage tests and response time tests in a realistic engine compartment mock-up. In addition, different types of sensors are tested separately for functionality and false alarms. System and components are also tested for durability related to corrosion, ageing, temperature variations, vibrations, shocks, EMC and ingress of dust and water. The method will complement SP Method 4912, “Method for testing the suppression performance of fire suppression systems installed in engine compartments of buses and coaches”, to increase fire safety of buses and other heavy vehicles. It is important that tested systems are complemented with a risk assessment of the real engine compartment before installation to provide answers both on how to best install the system and on how to scale the system based on the results from the engine compartment mock-up tests.

REFERENCES

15 June 2016].
The Development of FM Approval Standard 5970
Protection Systems for Heavy Duty Mobile Equipment

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ABSTRACT

The first edition of FM Global Approval Standard 5970 [1] was issued in August 2015. Heavy Duty Mobile Equipment (HDME) includes equipment used in mineral extraction, forest products, and other industries using specialized machinery that is not readily replaceable. Ignitable liquid fires in these vehicles, while not happening frequently, each represent substantial economic loss potential, with some mining equipment carrying replacement costs up to US$200 million. This standard is applicable to both off-road and road-licensed equipment.

Traditionally, the bulk of certifications for these fire extinguishing systems had been conducted to standards focused on the type of extinguishing agent employed. This led to separate fire extinguishment protocols for different agents, i.e. dry and liquid agents. In the past decade, some manufacturers began to use combined agent systems for this application to provide rapid extinguishment and cooling of hot surfaces to prevent reignition. None of the existing standards addressed these multi-agent systems. Accordingly, it was decided to develop a test protocol focused on the hazard, rather than the suppressant.

The Approval Standard includes the fire extinguishment protocols developed by FM Global’s Research Division, which consists of two test approaches. The first addresses engine compartment fires. The test configuration represents a congested engine compartment. Typically, such areas have been protected by pre-engineered systems. Both the compartment size and ventilation rate were selected at the high end of those on these vehicles. The concept is that an extinguishing system adequate for large, highly vented compartments will be adequate for smaller compartments with lower ventilation rates. A paradigm for scaling system capacity and discharge rate, based upon compartment size and airflow rate has been included.

The second approach uses six different single nozzle tests to assess range versus area of coverage and the appropriateness of the system manufacturer’s design recommendations. It is intended to allow more flexibility in system design. Both groups of tests assess the ability to extinguish spray, spill, and pool fires. Additionally, testing for both approaches is conducted under conditions of both significant airflow and still air. Success in all tests is required without repositioning of nozzles to accommodate the presence or absence of air movement.

The standard has been written to accommodate all extinguishing agents, dry, liquid, foam, mist, and gaseous and allows for the evaluation of multiple agent systems. Further, the standard includes protocols for evaluating system components for durability and practicality under a variety of conditions specific to the vehicle’s environment and maintenance procedures. Lastly, the standard integrates the evaluation of detection and control systems in addition to agent storage, release, and distribution systems.
KEYWORDS

mobile equipment, protection systems, test methods

INTRODUCTION

FM Global Property Loss Prevention Data Sheet 7-40 [2] recommends using sprinkler systems, or special protection systems which employ foam, dry chemicals or gaseous extinguishing agents for the protection of off-road vehicles and heavy duty mobile equipment (HDME). Historically, the fire extinguishing performance of FM-Approved special protection systems has been evaluated according to protocols provided in UL 1254, Pre-Engineered Dry Chemical Extinguishing System Units [3], AS 5062, Fire Protection for mobile and transportable equipment [4], and FM Approval Standard 5130, Foam Extinguishing Systems [5]. For ignitable liquid fires, UL 1254 and FM 5130 consider only the pool fire hazard, although spray and spill fires are also among the hazards encountered in HDME and other vehicles. Further, ventilation effects on fire extinguishment appropriate to these hazards were not considered by any of these three standards. AS 5062 considers the spray fire hazard and reignition resistance, but does not lend itself well to evaluating non-liquid agents.

Therefore, there has been uncertainty about the effectiveness of FM Approved systems in extinguishing some fire scenarios pertaining to off-road vehicles and mobile equipment. Consequently, in 2009, a research program was initiated in FM Global to develop a test protocol for the protection of HDME and other off-road vehicles. An Approval Standard incorporating the fire test protocol and evaluation requirements for system reliability was subsequently developed and designated as FM Global Approval Standard 5970.

One of the valuable resources evaluated in the development of the test protocol was the protocol developed by SP Technical Research Institute for the protection of buses and coaches [6]. This protocol uses a mock-up of a typical bus engine compartment. The effect of ventilation and reignition propensity are addressed. The fire scenarios include pool, spray, and dripping liquid fires. This test protocol was designed primarily for the evaluation of pre-engineered extinguishing systems.

FM Global insures many types of off-road vehicles and HDME used in excavation, construction, mining, and other industrial applications. Their intended functions determine the physical size, configuration, and range of components used, including many not found in the typical bus or motor coach. Fires can occur in the operator’s control area, engine compartment, electric generator and motor enclosures, transformers, hydraulic pump space, or fuel or lubricant pumps and piping. Except for the operator’s compartment, most fires will involve ignitable liquids in pool, spray, or spill scenarios, or combinations thereof.

The combustibles in the operator’s space are typically less challenging Class A materials. Where these exist in sufficient quantity to be of particular concern, protection can be addressed by the light hazard fire test protocol described in FM Approval Standard 5560, Water Mist Systems [7]. As a result, this hazard was not specifically addressed in Approval Standard 5970, except by reference to Approval Standard 5560.

Since off-road vehicles can vary widely in terms of size and configuration, a single approach would be impractical for the evaluation of fire extinguishing systems. A two pronged approach was devised to address this variability. Similarly to the current practice for water mist systems, pre-engineered systems were largely addressed by tests in a simulated engine compartment. It was observed that, despite their overall variability, different off-road vehicles exhibited similar engine compartments, varying more in size and ventilation than in configuration. Further, engine compartments tend to be congested. While the fire protection industry tends to designate systems for engine compartment protection as total flooding systems, a true total flooding action may not be realized in all the areas in
an engine compartment. These compartments are also subject to a wide range of air flows from still air to flows in the 6 m/s range. Therefore, a large 2.5m long by 1.5m wide by 1.0m high engine compartment mockup was developed, along with an air supply apparatus to provide air flow from 0 to 6m/s. The entire test mockup is used to evaluate pre-engineered engine compartment extinguishing systems in pool, spray, and spill fire scenarios. The results are then scalable by volume and air flow rate for smaller compartment sizes.

To allow assessment of nozzle capability, a variety of challenging single nozzle tests were devised to verify nozzle range and suppressant discharge criteria. This information is also essential to defining engineered system designs.- A survey was conducted of the past fire loss experiences to identify key fire scenarios for off-road vehicles. This information was used to design the test apparatus and determine the conditions for the single nozzle fire tests.

A series of fire tests was conducted using the engine compartment mockup and single nozzle test apparatus for three fire extinguishing systems, each used dry chemical, wet chemical, or compressed air foam. These tests confirmed the feasibility of the developed test protocols in evaluating the fire extinguishing effectiveness of different types of suppressants for the protection of off-road vehicles and mobile equipment.

Concurrently with this work, existing FM Approval Standards for other extinguishing systems were reviewed to select tests for component capability and durability that were appropriate for systems in HDME applications. Where necessary, additional appropriate test methods not previously employed by FM Approvals were identified, such as pressure washing and steam cleaning for components located in engine compartments and gravel bombardment for components located on the exterior of the vehicle.

Further, since these systems employ increasingly sophisticated supervisory, detection, and release systems, appropriate tests for the proper function, robustness, and durability of the related components and circuits were identified.
ENGINE COMPARTMENT FIRE EXTINGUISHMENT TESTS

The entire engine compartment test apparatus consists of an air supply system and an engine compartment mockup. The air supply system has the following components:

- A variable speed blower capable of producing 566 m³/min maximum air flow and equipped with an approximately 0.9 m long reducer, transitioning from the rectangular outlet of the blower to a 0.6 m diameter cross section
- A horizontal duct assembly 0.6 m in diameter
- An expander transitioning from the duct assembly to an opening 1.5 m wide x 1 m high
- The engine compartment mock-up
- A steel pan 1.52 m square and 100 mm high sitting on the laboratory floor, and centered below the compartment floor opening situated in the downstream half of the floor
The engine block mock-up is an enclosed rectangular box made of 3 mm thick stainless steel, measuring 2.11 m long by 1.15 m wide by 0.7 m high. The clearances between the engine block and compartment’s ceiling, floor, and front wall are approximately 150 mm and approximately 176 mm between the engine block and the compartment’s two side walls. The clearance between the engine block and back wall is slightly larger at 240 mm to accommodate the air filter drum. A 100 mm wide rectangular horizontal shield is located along the full length of each longitudinal side of the engine block, level with and contiguous with the top edge of the engine block.

Each manifold is provided with a propane line burner to raise its temperature to a nominal 540°C before the suppressant is discharged. The line burners are positioned 64 mm below the manifolds.

The following parameters are monitored or verified during each engine compartment test:

- Time and duration of preburn
- Air flow over the cross sectional area of the apparatus
- Temperature of the simulated exhaust manifolds
- Fuel flow rate
- Duration of suppressant discharge
- Time for extinguishment after beginning of discharge
- Time and duration of any reignition
- Quantity of suppressant discharged

While the test protocols are identified as either spray or spill fire tests, in each case pool fires typically ignite in the pan at the bottom of the apparatus, adding to the challenge of extinguishment.
Engine Compartment Spray Fire Test Protocol

Fuel spray fires are produced by injecting diesel fuel through a Monarch 58.7 l/h, or equivalent, nozzle. The nozzle is positioned approximately 175 mm below the manifold and angled 45° upward from the horizontal plane.

- The system manufacturer may position the discharge nozzles in any manner consistent with his specified design constraints. Dual agent systems may be installed for simultaneous or serial operation per the manufacturer’s specifications.
- The two simulated exhaust manifolds are heated to 540°C, +/-28°C with the propane burners.
- The diesel spray is initiated at 1 l/min.
- The propane feed to the burners is shut off after the diesel spray has ignited.
- The blower is started and the airflow brought to 6 m/s.
- Suppressant discharge is initiated after the air flow has been stabilized, but no sooner than 30s after the blower was started.
- If the fire is extinguished, diesel fuel spray is continued for an additional 30 seconds after extinguishment and any reignition noted.
- If the fire is not extinguished by the end of discharge, the diesel fuel spray is terminated after the end of discharge.
- If extinguishment is achieved, the test apparatus is thoroughly cleaned of all suppressant and the test repeated at zero air velocity.
- Successful extinguishment is required in both moving and still air conditions without repositioning of the suppressant nozzles.

Engine Compartment Spill Fire Test Protocol

A channel has been built into the top of the engine block to produce a consistent simulated spill of diesel fuel. The channel is 152 mm wide and 13 mm deep and centered on top of the engine block along the longitudinal centerline. Weirs 6 mm high are provided on both ends of the channel to maintain the fuel level. Stainless steel tubing feeds diesel fuel to the channel through a circular cup located at the channel center. Diesel then fills the channel and spills out at both ends.

- The suppressant nozzles shall be positioned in the same locations as for the engine compartment spray fire tests.
- The two simulated exhaust manifolds are heated to 540°C, +/-28°C with the propane burners.
- The diesel flow is initiated at 1 l/min.
- The propane feed to the burners is shut off after the diesel flow has ignited.
- The blower is started and the airflow brought to 6 m/s.
- Suppressant discharge is initiated after the air flow has been stabilized, but no sooner than 30s after the blower was started.
- If the fire is extinguished, diesel fuel flow is continued for an additional 30 seconds after extinguishment and any reignition noted.
- If the fire is not extinguished by the end of discharge, the diesel fuel flow is terminated after the end of discharge.
- If extinguishment is achieved, the test apparatus is thoroughly cleaned of all suppressant and the test repeated at zero air velocity.
- Successful extinguishment is required in both moving and still air conditions without repositioning of the suppressant nozzles.
SINGLE NOZZLE FIRE EXTINGUISHMENT TESTS

There are six single nozzle fire extinguishment test scenarios. Because extinguishing systems are often not included in the design of HDME and off-road vehicles, attempts to retrofit them often result in well than ideal placement of one or more nozzles. Each scenario represents an identified fire condition for off-road vehicles and mobile equipment. These six scenarios are:

1. Spray fire with agent discharge obstructed by a hot object (such as engine exhaust piping).
2. Spray fire with agent discharge obstructed by a cluster of objects (such as hoses and cables).
3. Spray fire impinging on a surface at 90° to the direction of suppressant discharge.
4. Flowing fuel and pool fire partially obstructed by engine block.
5. Pool fire partially obstructed by vertical cylinder (such as an air filter).
6. Combination spray and pool fire.

The following figures illustrate sequentially the numbered single nozzle fire extinguishment scenarios.

**Figure 3** Single Nozzle Scenario 1

**Figure 4** Single Nozzle Scenario 2
Figure 5  Single Nozzle Scenario 3

Figure 6  Single Nozzle Scenario 4
Test Procedure and Data Collection for Single Nozzle Fire Extinguishment Tests

The test procedure for single nozzle tests is provided in Table 1 below.

<table>
<thead>
<tr>
<th>Action</th>
<th>Fire Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>The simulated exhaust manifold is heated to 540°C, +/−28°C</td>
<td>1, only</td>
</tr>
<tr>
<td>The diesel spray is initiated at 1 l/min.</td>
<td>1, 2, 3, &amp; 6, only</td>
</tr>
<tr>
<td>The propane feed to the burners is shut off after the diesel spray has ignited</td>
<td>1, only</td>
</tr>
<tr>
<td>The fuel spray or pan is ignited with a propane torch and extended burner wand</td>
<td>All, except 1</td>
</tr>
<tr>
<td>The blower is started and the airflow brought to 6m/s</td>
<td>All</td>
</tr>
</tbody>
</table>
Successful extinguishment is required in both moving and still air conditions without repositioning of the suppressant nozzles.

The following parameters are monitored or verified during each test:

- Air flow over the cross sectional area of the apparatus
- Temperature of the simulated exhaust manifold (Scenario 1, only)
- Fuel flow rate (Scenarios 1, 2, 3, and 6, only)
- Duration of suppressant discharge
- Time for extinguishment after beginning of discharge
- Time and duration of any reignition
- Quantity of suppressant discharged

### TRANSLATION OF FIRE EXTINGUISHMENT TEST RESULTS TO SYSTEM DESIGN

All fire extinguishment tests shall be conducted with systems conforming to the manufacturer’s original design manual, which may require revision to conform to test results based upon the following precepts:

- Engine compartment fire tests shall be used to determine baseline static and dynamic suppressant volume requirements for compartments.
- Static volume requirement shall be, at minimum, the total rate of flow of suppressant into the space (by weight or volume) divided by the compartment’s free volume, approximately \((2\text{ m}^3)\).
- Dynamic volume requirement shall be, at minimum, the total rate of flow of suppressant into the space divided by the volume flow rate of air through the space, approximately \((365\text{ m}^3/\text{min})\).
- These baseline values shall be used by the manufacturer to scale protection for larger or smaller volumes and air flow rates, with the more conservative of the two values so derived used to determine the design.
- The single nozzle fire extinguishment tests shall be used to determine the area of coverage and range for individual nozzles.
- The manufacturer’s design manual shall be reviewed to verify that these parameters have been incorporated into the design requirements.
FURTHER WORK

An FM Approval Standard is a living document. For a new standard, such as 5970, the first examinations conducted per the standard reveal opportunities for improvements and corrections. FM Approvals is currently working with several manufacturers attempting to secure FM Approval for their HDME protection systems for the first time, as well as re-examining all currently FM-Approved systems to the requirements of the new standard.

This provides a much larger portfolio of data than was available from the Research program that informed the development of the standard. Accordingly, the various engineering decisions resulting from the new information are logged and will be incorporated in a revised edition of the standard by the end of this process. FM Approvals plans to develop an ANSI version of this standard.

REFERENCES


Motorcoach Fire Safety Evaluation – Fire Hardening

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ABSTRACT
The Department of Transportation (DOT) National Highway Traffic Safety Administration (NHTSA) awarded a contract to Southwest Research Institute (SwRI) to conduct research and testing in the interest of motorcoach fire safety. The goal of this program was to develop and validate procedures and metrics to evaluate current and future detection, suppression, and exterior fire-hardening technologies that prevent or delay fire penetration into the passenger compartment of a motorcoach - in order to increase passenger evacuation time.

The results of the engine compartment and wheel well research have been previously published and presented [1]. This paper will focus on the fire-hardening aspects of the research, the results of which have not yet been published in detail.

KEYWORDS: Motorcoach, Fire Safety, Fire Hardening

INTRODUCTION
Regulatory Background
The Department of Transportation (DOT) Motorcoach Safety Action Plan of 2009, charges NHTSA to evaluate the feasibility of more-stringent flammability requirements for interior and exterior materials, and regulations requiring installation of fire detection and protection systems.

The Motorcoach Enhanced Safety Act of 2011 calls for standards to improve fire safety through evaluation of flammability criteria for exterior components of motorcoaches, smoke suppression to prevent inhalation of toxic gasses through improved fire resistance of interior components covered under FMVSS 302, prevention of and resistance to wheel well fires to mitigate propagation into the passenger compartment, and evaluation of automatic engine compartment detection and suppression systems.

Based on this legislation, NHTSA funded research to develop test apparatuses and test procedures to evaluate candidate fire detection and suppression systems for motorcoach engine compartments, and hot wheel warning systems to prevent tire fires in the wheel well. In addition, the funding included additional work on the fire hardening task to supplement previous work performed for NHTSA.

Previous Fire Hardening Work
In 2009 NHTSA funded the National Institute of Standards Technology (NIST), Building and Fire Research Laboratory (BFRL) to conduct research [2] to:

1. Understand the development of motorcoach fires and its subsequent spread into the passenger compartment,
2. Evaluate and identify bench-scale material flammability test methods,
3. Test the effectiveness of fire hardening of motorcoach exterior components around the wheel well, and
4. Assess tenability within the passenger compartment in the event of a wheel-well fire.
With respect to fire hardening, they conducted large/full-scale tests on a motorcoach assembly and measured the time it takes for fire to penetrate into the passenger compartment from a wheel well fire (tire fire). In this research, several hardening materials were tested to see how the penetration time was affected by different materials and methods.

In their project, NIST looked at replacement of combustible motorcoach siding material above the wheel well and below the windows of the passenger compartment (fender and additional exterior siding panel). The replacement materials or modifications included steel, intumescent fire protection schemes (where a carbon foam is created to provide thermal insulation), and a fire plume deflector. While steel and the intumescent coating were effective at preventing or delaying fire spread into the passenger compartment, the fire plume deflector that would ideally direct the flame out and away from the bus was not.

One missing piece from the NIST work was a way to relate the times to fire penetration in full-scale experiments to a laboratory-scale test method, so that new products and materials could be evaluated for this application.

**Fire Hardening Research Objective**

The objective of the fire hardening task of this research project was to propose a standard test method that could be linked to the NIST work and could be used to evaluate potential fire hardening materials for this purpose.

**METHOD AND RESULTS**

**General Approach**

Several test methods were considered to evaluate suitability of materials for motorcoach fire hardening. The elements of the test methods that were considered in selecting a suitable test method included: cost of setup and/or to conduct test, scalability of test method, and the ability of the test method to be related to conditions seen in full scale tests.

One intermediate-scale test method was chosen and one bench-scale test method was chosen for this purpose. The same nominal materials that were tested by NIST were tested in these two apparatuses/procedures and the results are compared to obtain a relationship between small, intermediate and full-scale test data.

For organic solids, liquids, and gases, a nearly constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. An average value for this constant of 13.1 MJ/kg of O2 can be used for practical applications and is accurate with very few exceptions to within ±5%. Therefore, measurements of the oxygen consumed in a combustion system can be used to determine the net heat released. This technique, generally referred to as the “oxygen consumption technique”, is now the most widely used and accurate method for measuring heat release rate (HRR) in experimental fires.

The HRR of the NIST experiments was measured with the oxygen consumption technique and so this is the same method used in the two standard test procedures discussed below. It is expected that this particular quantity would able to be scaled between the NIST data and the standard test method data.

**Cone Calorimeter**

The Cone Calorimeter is a bench-scale test apparatus, which measures the rate of heat release of materials and products under a wide range of conditions using the oxygen consumption technique. A schematic of the instrument is shown in Figure 1. Other useful information obtained from Cone Calorimeter tests includes time to ignition, mass loss rate, smoke production rate, and effective heat of
In the Cone Calorimeter, a square sample measuring $100 \times 100$ mm (4 × 4-in.) is exposed to the radiant flux of an electric heater. The heater is in the shape of a truncated cone and is capable of providing heat fluxes to the specimen in the range of 0–100 kW/m².

**Figure 1** Schematic of the Cone Calorimeter Apparatus.

The Parallel Panel Fire Test exposes two 0.6 × 2.4-m samples placed 0.3-m apart to the effects of a 0.3 × 0.6-m propane gas sand burner with an output of 60 kW for a 10-min duration followed by a 2 min observation period. The panel assembly is located on a load cell capable of measuring mass loss throughout the test. The test is performed under a calorimeter in order to measure heat release and smoke release rates during the test. Additionally, heat flux is measured at a height of 1.2-m on the surface of one panel at the vertical centerline. In these specific tests, the backside temperature of the test assembly was also measured, although this is not required. Visual measurements of the flame height are recorded using digital video and still photographs.

The heat release rate is measured using the oxygen consumption technique. The smoke release rate is determined by the measured light obscuration in the exhaust duct using a vertically-oriented, white-light extinction photometer located close to the gas sampling point. Figure 2 shows a schematic of the parallel panel test apparatus.
Fire Hardening Test Plan

Several materials were tested in both the Cone Calorimeter and the Parallel Panel test apparatus. NIST performed four tests that utilized glass-reinforced plastic (GRP) exterior paneling. NIST conducted an additional test with the GRP coated with Pitt Char XP and an additional test with a sheet steel panel, instead of a combustible material, like the GRP panel. For this project, the same nominal materials used in the NIST work were tested, along with a few additional materials.

The following materials were used for fire hardening testing:

- GRP Sandwich Panel – donated by motorcoach OEM
  - Nominal thickness: 8.85 mm
  - Color: gray outer with white foam core
- Galvanized Sheet Metal Panel – donated by motorcoach OEM
  - Nominal thickness: 1.28 mm
  - Color: Silver with Green primer paint
- Gypsum Wallboard – obtained locally
  - Nominal thickness: 16 mm
  - Color: pink paper face
- Red Oak Plywood – obtained locally
  - Nominal thickness: 18.72 mm
  - Color: natural wood (brown/tan)
- Pitt Char XP – obtained locally from a PPG, Industries, Inc. distributor
  - Each of the four materials above was tested with and without a Pitt Char XP coating.
  - PPG application instructions for troweling on the coating were followed and a nominal 150-200 mil (4-5 mm) coating thickness was applied to each material.
Cone Calorimeter Test Results

Cone calorimeter heat release rate testing was performed at an incident heat flux of 50 kW/m². Additional ignition testing was conducted to determine the critical heat flux for ignition (CHF) and the material’s thermal response parameter (TRP).

The TRP is a measure of the thermal inertia of a material (product of thermal conductivity, density, and specific heat). It is calculated by plotting the inverse square root of the ignition time versus the external heat flux and fitting a line through the data points. The inverse of the slope of this line is defined as the TRP. The fire propagation index (FPI) is a measure of full-scale flame spread propensity and is calculated based on ignition data (TRP) and HRR data (peak HRR). In general, fire performance is inversely proportional to the FPI. In other words, products with bad fire performance (high flame spread) typically have high FPI values. The FPI is calculated based on Eq. (1):

\[
FPI = \frac{1000(0.042 \cdot Q_{\text{peak}})^{0.42}}{\text{TRP}}, \quad \text{where} \quad Q_{\text{peak}} = \text{peak heat release rate in cone at 50 kW/m}^2 \text{ (kW/m}^2); \quad \text{TRP} = \text{thermal response parameter (kW-s}^{1/2}/\text{m}^2); \]

Table 1 provides a summary of the cone calorimeter test results.

<table>
<thead>
<tr>
<th>Test Material</th>
<th>CHF (kW/m²)</th>
<th>TRP (kW-s^{1/2}/m²)</th>
<th>HRR_{peak} (kW/m²)</th>
<th>FPI (m^{5/3}/kW^{2/3}-s^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>13</td>
<td>446</td>
<td>342</td>
<td>5.45</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>ND</td>
<td>ND</td>
<td>9</td>
<td>ND</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>33</td>
<td>286</td>
<td>101</td>
<td>5.66</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>16</td>
<td>256</td>
<td>300</td>
<td>9.09</td>
</tr>
<tr>
<td>Coated with Pitt Char XP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>19</td>
<td>270</td>
<td>156</td>
<td>6.93</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>19</td>
<td>244</td>
<td>151</td>
<td>7.59</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>22</td>
<td>238</td>
<td>153</td>
<td>7.81</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>21</td>
<td>270</td>
<td>148</td>
<td>6.81</td>
</tr>
</tbody>
</table>

ND: not determined, this material is noncombustible, so these parameters cannot be calculated for the uncoated specimens.

It can be noted from Table 1 that the Pitt Char XP coating is able to reduce the peak heat release rate for all the materials that have some combustibility. The sheet metal and gypsum wallboard peak heat release rate actually increases with the Pitt Char XP coating application since these materials are inherently non-combustible (with exception to the paper face on the gypsum wallboard and very thin primer paint coat on the sheet metal).

It can be observed that for this data set, the FPI term does not seem to be a good indicator of better fire performance. This is primarily due to the fact that the Pitt Char XP coating is combustible and will ignite and spread flame. This skews the data slightly as the TRP typically goes down for the coated materials, but not as much as the heat release rate goes down, which inflates the FPI term.
In addition, materials that are non-homogeneous, and in particular, have a combustible top layer over a noncombustible substrate (e.g., gypsum wallboard with paper face), tend to be outliers in the FPI approach, since the ignition and heat release rate data for these materials is not really indicative of the fire performance over a longer duration. For a larger data set with more homogeneous materials or more materials with fire protective coatings, which could be compared to the Pitt Char XP coating, it is expected that FPI would be a better indicator of relative fire performance.

A more obvious benefit of the Pitt Char XP coating in this data set can be seen for combustible materials, such as the GRP and red oak plywood. In the case of these materials, the peak heat release rate can be reduced by a factor of 2.

**Parallel Panel Test Results**

Parallel Panel testing was conducted in general accordance with FM 4910. All samples were installed against a calcium silicate substrate and plywood backing. Heat flux was measured 1.2-m from the bottom of one of the panels under test and an additional thermocouple was installed on the backside of the test assembly 1.2-m from the bottom of the same panel.

Table 2 provides a summary of the parallel panel test results.

<table>
<thead>
<tr>
<th>Test Material</th>
<th>HRR\text{peak} (kW)</th>
<th>Time to HRR\text{peak} (s)</th>
<th>Peak Heat Flux (kW/m²)</th>
<th>Peak Backside Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>1196</td>
<td>146</td>
<td>111</td>
<td>100</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>6</td>
<td>95</td>
<td>4</td>
<td>54</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>5</td>
<td>96</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>365</td>
<td>113</td>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>Coated with Pitt Char XP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP Panel</td>
<td>82</td>
<td>184</td>
<td>41</td>
<td>65</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>72</td>
<td>187</td>
<td>28</td>
<td>62</td>
</tr>
<tr>
<td>Gypsum Wallboard</td>
<td>106</td>
<td>193</td>
<td>35</td>
<td>87</td>
</tr>
<tr>
<td>Red Oak Plywood</td>
<td>66</td>
<td>148</td>
<td>22</td>
<td>38</td>
</tr>
</tbody>
</table>

It can be noted from Table 2 that the Pitt Char XP coating has a similar effect on the materials in intermediate-scale. It increases the peak heat release rate for mostly noncombustible materials, but reduces it dramatically for combustible materials. Figure 3 – Figure 5 show a few selected photographs from the fire hardening testing in the Parallel Panel test apparatus.
Figure 3. Parallel Panel Test – Left: Setup, Right: Peak HRR (Uncoated GRP Material Shown).

Figure 4. Parallel Panel Test – Left: Setup, Right: Peak HRR (Uncoated Sheet Metal Material Shown).
DATA ANALYSIS

NIST Testing

Table 3 provides a summary of the tests that NIST conducted and the results.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Material</th>
<th>HRR_{peak} (kW)</th>
<th>Time to HRR_{peak} (s)</th>
<th>HRR / Time to Peak (kW/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GRP Panel (Tag Axle)</td>
<td>1175</td>
<td>280</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>GRP Panel (Drive Axle)</td>
<td>1480</td>
<td>363</td>
<td>4.1</td>
</tr>
<tr>
<td>3</td>
<td>Galvanized Sheet Metal</td>
<td>391</td>
<td>2464</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>GRP Panel Coated with Pitt Char XP</td>
<td>1043</td>
<td>1946</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>GRP Panel with Steel Deflector above Fender</td>
<td>1136</td>
<td>588</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>GRP Panel (Tag Axle – Tenability Experiment)</td>
<td>950</td>
<td>679</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Figure 6 plots the time to penetrate the passenger compartment (through the window) versus heat release rate. It can be noted that there is not a clear demarcation in terms of heat release rate between good performers and bad performers, with respect to gaining time to penetration. However, Figure 7 plots the time to penetration versus the ratio of heat release rate to the time to penetration. In this plot it can be observed that there seems to be a demarcation between good and bad performers for an approximate ratio of HRR/time=1 (kW/s).
Figure 6  NIST Data Plot – Time versus HRR.

Figure 7  NIST Data Plot – Time versus HRR/Time.
Predicting Full-Scale Test Results

Table 4 shows a comparison of data between the NIST results and testing in the cone calorimeter and parallel panel test apparatuses. Figure 8 and Figure 9 show plots of the parallel panel and cone peak heat release rate versus NIST time to penetration.

**Table 4  Comparison of NIST, Parallel Panel and Cone Test Results.**

<table>
<thead>
<tr>
<th>Test Material</th>
<th>Parallel Panel HRR\text{peak} (kW)</th>
<th>Cone Calorimeter HRR\text{peak} (kW/m²)</th>
<th>NIST Time to Penetration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRP Panel (Tag Axle)</td>
<td>1196</td>
<td>342</td>
<td>280</td>
</tr>
<tr>
<td>GRP Panel (Drive Axle)</td>
<td>1196</td>
<td>342</td>
<td>363</td>
</tr>
<tr>
<td>Galvanized Sheet Metal</td>
<td>6</td>
<td>9</td>
<td>2464</td>
</tr>
<tr>
<td>GRP Panel Coated with Pitt Char XP</td>
<td>82</td>
<td>156</td>
<td>1946</td>
</tr>
<tr>
<td>GRP Panel with Steel Deflector above Fender</td>
<td>1196</td>
<td>342</td>
<td>588</td>
</tr>
<tr>
<td>GRP Panel (Tag Axle – Tenability Experiment)</td>
<td>1196</td>
<td>342</td>
<td>679</td>
</tr>
</tbody>
</table>

![Figure 8](image-url)  Parallel Panel Peak Heat Release Rate versus NIST Time to Penetration.
CONCLUSIONS

There is a limited amount of full-scale data to rigorously evaluate this relationship between cone calorimeter and parallel panel test results with the results NIST obtained. However, it seems likely that a relationship does exist and could be refined if more full-scale data were made available. As a screening tool, a limit between propagating and non-propagating performing materials may be on the order of 200 kW in the Parallel Panel test or 200 kW/m² in the Cone Calorimeter test. The final report for this research project has been published by NHTSA and available to the public [4].

REFERENCES

Fire Risks of Electrical Vehicles in Underground Car Parks

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ABSTRACT

In a pre-study in 2015, SP Fire Research AS conducted a literature survey. This pre-study presented an overview of challenges related to the fast introduction of electric vehicles (EVs), with focus on underground car parks. Some of the challenges are related to gaps in knowledge about how an EV fire evolves and should be extinguished in enclosed space. SP Fire Research AS is now further looking into these challenges in an ongoing main study that will be finished in 2016. The importance of studying this topic, and the main conclusions from the pre-study are presented in this paper.

KEYWORDS: Li-ion battery, electrical vehicles, car parks, enclosed fires.

BACKGROUND

The number of electrical vehicles (EVs) in Norway has been doubled each year since 2010, and has now passed 100 000 vehicles, which is about 3 % of the total vehicle fleet. The prognosis indicates that there will be around 200 000 Norwegian registered EVs in 2020, and from 2025 all new cars shall be zero-emission cars. Due to the lack of available parking areas above ground in the large cities, more vehicles are parked in underground car parks. The rapidly growing number of EVs introduces a need for evaluating fire risks in underground car parks, and it is crucial that building regulations are relevant and up to date.

LI-ION BATTERIES

Lithium-ion batteries are the most used battery-technology in electrical vehicles. Development of battery technology is continually increasing the energy density of the batteries and thus the total energy stored in the vehicles. All the large car manufacturers have now introduced their own electrical vehicle model, and the variety of different technologies and battery capacities on the market is extensive.

Thermal runaway

If a Lithium-ion battery is physically damaged, overcharged or exposed to external heat, this may trigger heat-producing chemical reactions in the battery. If the produced heat raises the internal battery cell temperature above a certain level, a process called thermal runaway (TR) occurs. The TR temperature threshold varies for different battery technologies, but is normally between 130 – 200 °C. TR is a highly exothermic reaction which produces heat. The amount of produced heat may be sufficient to set the flammable electrolyte on fire. TR in one cell can then initiate TR in the neighboring cells [1]

TR is a chemical reaction that cannot be stopped. It is, however, important to cool down the battery pack to inhibit the spread of TR to neighboring cells. Due to the battery’s protective casing and the
placement of the battery pack in the vehicle, it is challenging to get the water to cool down the cells. Most of it runs off, and the water’s cooling properties is not utilized to its full extent.

**Li-ion battery fire tests**
A few full scale tests have given valuable information about to should expect when an EV battery pack is on fire. NFPA concluded that it takes longer time and more water to fully extinguish an EV fire compared to a fire in a vehicle with conventional fuel. Besides, a fire in a Li-ion battery pack may reignite several hours after termination of extinguishment [2]. DEKRA [3,4] showed in their tests that by adding additives to the water, the amount of water needed was significantly reduced, due to increased wettability or higher viscosity. INERIS compared the heat release rate (HRR) of an EV with a similar sized internal combustion engine vehicle (ICE), and found that the HRR was comparable [5]. NFPA has additionally performed a full scale fire test on a battery storage system [6], which showed that a good battery design may prevent a fire to spread from one section to the adjacent ones. Although this system has many of the same applications and safety barriers as a vehicle battery, it is not completely the same.

Due to the low number of published fire tests of full scale batteries and EVs, it is therefore several unanswered questions related to how an EV fire may occur, how it may develop and how it best should be put out.

**CAR PARK FIRES**
A fire in an underground car park can be dramatic and challenging for fire fighters on site, regardless of what kind of fuels that are involved. The entrance of a typical car park is normally too low for fire trucks to enter, which makes the working distance for fire fighters significantly longer than for an outdoor car fire. In addition, the restricted view from a large amount of smoke makes it challenging for fire fighters to efficiently control the fire and evacuate people.

Over the last decades the cars have undergone a considerable change with regard to materials used. The incombustible steel in the cars have been thoroughly replaced by different types of combustible plastics [7]. Statistics from car park fires involving older cars, shows that the majority of fires involve only one car [9]. However, the increase of combustible material in new cars leads to a higher heat release rate and a higher probability of a car fire to spread to neighboring vehicles [10,11]. Several severe car park fires during the last decades have been reported ([12], [13], [14], [15], [16]) and the need for evaluating the safety of old car parks when new fuels are introduced has been addressed.

**RESULTS FROM THE STUDY**
The study has assessed the challenges related to EVs and underground car parks from a Norwegian perspective. Some of the challenges found in this study may be relevant only for Norway, while other may be more general.

**Building regulation in Norway**
The car park buildings in Norway, not unlike in other countries, holds a variety of different sizes, geometries and are built over a period of several decades. The building regulations have changed during this period, and the use of passive and active fire protection in these garages therefore varies. New and stricter regulations prohibit large car parks without sprinkler, and ensure better working conditions for fire fighters. However, the majority of the car parks are built before these regulations were implemented, and the question is whether or not EVs in car parks pose a greater fire risk than ICE vehicles, and whether or not charging of EVs affect the risk.
Knowledge gaps and challenges

The lack of information and experience on how an EV will behave in a car park fire with regard to heat release rate and extinguishing time causes skepticism and uncertainty among users as well as firefighters.

1. The battery sizes (16 – 23 kWh) that have been used in most of the published full scale fire tests, are not representative for the largest batteries on the market today. Tesla Model X, for instance, is delivered with batteries up to 90 kWh. The question is therefore whether or not these tests are relevant for the larger battery sizes and different battery chemistries on the market.

2. There is a lack of data on how fast an EV fire may evolve, how good the safety mechanisms of the battery works and how much heat a modern EV releases.

3. Tests indicate that extinguishing an EV fire may require more water and longer time than an ICE. However, how much water that is needed, what extinguishing techniques that are best and how long time it will take to extinguish different car models is not completely revealed.

4. If a battery is exposed to heat above the TR-temperature limit, e.g. in an enclosed fire in a car park, TR will eventually be initiated, but there are no published full scale tests that reveal how fast TR will occur in a typical car park fire.

5. Based on statistics over years we know that an automatic sprinkler is an effective measure for protecting a building against fire. The sprinkler does not necessarily extinguish the fire, but cools down the hot fire gases and thereby reduces the chance for the fire to spread to an adjacent vehicle. Studies and several real fires [10,11,17] confirm that an appropriate installed sprinkler cools down a fire, also for modern ICE-vehicles. However, there is no published information on how an EV fire will behave when impacted by a sprinkler.

In order to ensure safe parking of EVs in underground car parks, it is important to fill the above mentioned knowledge gaps. This would affect a range of aspects, including the dimensions of sprinkler systems, fire barriers in the building, and tactics for fire fighters etc. The lack of information has led to the following concerns and challenges:

- Many fire brigades, especially the smaller ones, have not got the information and education they need to handle a fire or a collision where EVs are involved. This has led to a few episodes where an EV fire has not been extinguished, due to the misconception that one cannot use water in an EV fire.

- The increasing number of people in Norway owning EVs also need access to charging facilities. As many people in Norway live in cooperative housing and share an underground car park, concerns about fire safety has caused a massive debate whether or not such chargers should be allowed in the car parks. There are clear guidelines for how an EV home charger should be installed, but no guidelines on where it is allowed to be installed. The result is that some cooperative houses have accepted home chargers, while others have not.

- Another issue arises when more and more home chargers are installed in cooperative housings, because the power lines into the flats are not designed for the needed currents when lots of cars are charging simultaneously.

FURTHER WORK

This study has pointed out that there is a need for more research on several topics regarding new EVs in underground car parks, and there is also a need to better disseminate information that is already available.
available. New car trends and new technologies should be continuously followed by full scale tests to reveal knowledge of the related fire risks and how they should be dealt with.

SP Fire Research will continue to look into challenges related to EVs and other new trends related to Li-ion batteries, like battery storage systems both onshore and offshore.

Acknowledgement
The study was funded by the Norwegian Directorate for Civil Protection and the Norwegian Building Authority.

REFERENCES

5. Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle. 2014 Apr. Report No.: HAL Id: ineris-00973680.
Qualitative Risk Analysis of Dangerous Goods with Alternative Propellants

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ABSTRACT
This qualitative risk analysis of dangerous goods transports with alternative propellants was ordered by the Swedish Civil Contingencies Agency (MSB). Scenario combinations consisted of five alternative fuels, six accident scenarios and five types of dangerous goods cargo. The alternative fuels were: methane, hydrogen, ethanol, methanol and dimethyl ether. The accident scenarios consisted of refuelling, fire in tire or engine, tunnel accident, road collision and sabotage of fuel tank. The dangerous goods were limited to: ammonium nitrate, petrol/diesel, methane, ethyl chloride, and EX/II cargo as defined in the ADR regulation. The main identified risks are due to the risk of pressure vessel explosion of gaseous fuels as it: 1) Threatens to detonate explosive load or ammonium nitrate. 2) Cause rescue service to take a defensive approach which will lead to larger consequences. Since there are sustainable liquid fuel alternatives such as bio diesel, this may be a better choice for dangerous goods transportation.

KEYWORDS: Risk analysis; dangerous goods; alternative propellants

INTRODUCTION
Worldwide governments are implementing goals and policies to decrease the use of fossil fuels and to reduce greenhouse gas emissions. The EU is considering allowing alternative propellants for dangerous goods transportation by road. The Swedish Civil Contingencies Agency (MSB) felt that it was not yet clear whether alternative propellants, e.g. natural gas, biodiesel or hydrogen, would introduce new or emerging risks. Therefore MSB ordered a qualitative risk analysis of dangerous goods transports with alternative propellants from SP.

METHOD
The project was limited to pre-selected scenarios, propellants and dangerous goods cargo by the client MSB. The following dangerous goods cargos were included in the study: explosives, diesel/petrol, methane, chloroethane, and ammonium nitrate. The following alternative propellants were included in the study: methane (CNG and LNG), hydrogen (H2), ethanol, methanol, and dimethyl ether. The following scenarios were studied: refueling, fire in tire or engine, tunnel accident, road collision and sabotage of fuel tank.

The project was structured in five steps:
1. Analyse chemical hazards from combining propellants with dangerous goods
2. How common are the different substances and how frequent do different types of accidents occur?
3. Consequence analysis that investigate how the alternative propellants behave in case of release and/or ignition
4. Qualitative scenario risk analysis where probabilities and consequences are estimated for all combinations of: dangerous goods, propellant and scenario listed above. The probabilities and consequences were estimated on a five graded scale compared with the current situation with diesel propellant.
5. Recommendations
RESULTS
Compared to diesel, no emerging risks were identified with regards to the mixture of propellant and dangerous goods.

From Swedish statistics it is confirmed that the identified accident scenario with fire in tire or engine and road collisions with dangerous goods transports occur at a rate of about once per year. Refuelling with conventional liquid fuels is very safe with few incident sand no serious accidents. Refuelling with new fuels need some time before it becomes safer and safer [1-4]. Based on over 1500 international dangerous goods accident up to 2004 there has been five accidents in road tunnels of which four involved a fire [5]. An international survey identified 50 CNG pressure vessel explosions (excluding misuse) in the period 1976-2010. Most occurred during refuelling or fire exposure [6]. A pressure vessel explosion of a 130 L CNG-tank at 200 bar can be approximated with a detonation of 1,85 kg TNT (8.7 MJ). Windows will brake within a 30 m radius (50 mbar) and death can occur within a radius of 12 m (140 mbar) [7]. This means according to [8, 9] that a safe distance between tank and load would need to be 18 m to ensure that ammonium nitrate does not detonate. Many types of explosive loads can be expected to be even more sensitive than ammonium nitrate which is actually not classified as an explosive in the ADR regulation.

Scenario descriptions for each scenario was generated and analyzed. A main difference between liquid fuels and gaseous fuels concerns the intervention of the rescue service. They will take a much more defensive tactic in cases when there is a risk of a pressure vessel explosion, possible followed by a BLEVE for LNG and DME or a gas cloud explosion for CNG and H2.

CONCLUSIONS
The main identified risks compared with diesel as propellant are due to the risk of pressure vessel explosion of gaseous fuels (CNG, LNG, DME or H2). There are primary two reasons for this increased risk: 1) Pressure vessel explosion of gaseous fuels threatens to detonate explosive load or ammonium nitrate. 2) Due to the risk of a pressure vessel explosion following a fire, the rescue service often chooses to take a defensive approach which will lead to larger consequences. Since there are sustainable liquid fuel alternatives such as bio diesel, this may be a better choice for dangerous goods transportation.

REFERENCES
1. MSB, Analys av olycks- och tillbudsrapporter - Studie av rapporter i samordnat olycks- och tillbudsrapporteringsystem (SOOT) 2014. 2015, Myndigheten för samhällsskydd och beredskap.
7. Perrette, L. and H.K. Wiedemann. CNG buses safety : learnings from recent accidents in France and Germany. in Society of automotive engineer world Congress. 2007. Detroit,United States.
Gas Emissions from Lithium-Ion Battery Cells Undergoing Abuse from External Fire

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ABSTRACT

Heat release rate, total heat released and toxic gas emissions were measured during exposure of commercial lithium-ion (Li-ion) battery cells to an external propane burner fire. Hydrogen fluoride (HF) was found in all tests and the released HF emissions measured via online FTIR range between 12-81 mg/Wh. Gas-washing bottles were used as a secondary measurement technique in one of the tests. The gas washing bottle and the FTIR measurements were in the same order of magnitude proving the usefulness of the FTIR technique even if there is an accumulation of HF in the filters used in the beginning of the test. The HF release for a large battery pack exposed to fire could thus in a worst case scenario result in a very large volume of toxic gases.

KEYWORDS: lithium-ion battery, gas emission, toxic gases, safety, fire, HRR

INTRODUCTION

Currently Li-ion has taken the position as the dominant choice for batteries used in portable battery powered consumer products. Li-ion batteries have also been introduced in electrified vehicles, in the electrical power grid and in ships. The Li-ion battery has attractive properties in form of power and energy densities, long life time, fast chargeability and no memory-effect, but has some potential drawbacks when it comes to safety.

The high energy densities of Li-ion batteries give potential for a rapid de-energizing. Additionally, the electrolyte used in Li-ion batteries is flammable. Compared to many other battery technologies, the Li-ion battery requires substantial efforts in order to manage its intrinsic safety shortcomings. The voltage and temperature ranges must be monitored and controlled. The Li-ion cell must be protected against physical damage (e.g. penetration and deformation) and from short circuit. In case of a severe failure, the Li-ion cell can undergo a thermal runaway which is a rapid exothermic reaction resulting in a fast temperature increase, gassing, fire and potentially an explosion. Furthermore, the gases released from the cell are toxic; of special interest is the production of hydrogen fluoride (HF) [1-3]. This work presents fire tests that have been performed on commercial Li-ion cells where HF is measured.

EXPERIMENTAL SET-UP

The Single Burning Item apparatus (SBI) was used to measure typical fire characteristics, e.g. Heat Release Rate (HRR), CO and CO₂ production in addition was HF measured. Multiple commercial Li-ion cells were exposed to external fire by a 16 kW propane burner. Table 1 shows the details of the cylindrical and pouch cells, including state-of-charge (SOC), used in the four tests, A-D, performed. The cells were not electrically connected to each other and not under electrical load during the tests. The cylindrical cells were placed in boxes to protect from flying projectiles and the LTO cells were both fastened to each other and fastened to the wire grating with steel wire, as seen in Figure 1. For test D the center temperature between the two cells and both cell voltages (CV) were measured every second. Gases were measured online by FTIR, particular interest was given to the emission of hydrogen fluoride (HF). The FTIR gave one spectrum every 12 seconds based on 10 scans. Detailed descriptions on the experimental set-up can be found in Larsson et. al. [1].
Table 1: Test overview.

<table>
<thead>
<tr>
<th>Test</th>
<th>Cell type</th>
<th>No. of cells</th>
<th>Nom voltage (V)</th>
<th>Total nom capacity (Ah)</th>
<th>Electrode chemistry</th>
<th>Cell packaging</th>
<th>SOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>K2 LFP26650EV</td>
<td>9</td>
<td>3.2</td>
<td>28.8</td>
<td>Carbon – LFP</td>
<td>Cylindrical</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>K2 LFP26650EV</td>
<td>9</td>
<td>3.2</td>
<td>28.8</td>
<td>Carbon – LFP</td>
<td>Cylindrical</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>Lifetech X-1P</td>
<td>5</td>
<td>3.3</td>
<td>40</td>
<td>Carbon – LFP</td>
<td>Cylindrical</td>
<td>100</td>
</tr>
<tr>
<td>D</td>
<td>Leclanché LTO</td>
<td>2</td>
<td>2.3</td>
<td>60</td>
<td>LTO – NCO</td>
<td>Pouch</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 1: Experimental setup before burner start for test B (left), test C (mid) and test D (right).

In addition to the FTIR measurements, gas-washing bottles were used in test D in order have a second measurement technique to sample the total amount of released fluorides. The assumption here was that the absolute majority of water soluble fluorides would be HF. Two gas-washing bottles, each containing 40 mL of a carbonate/bicarbonate buffer solution, were connected in series. The flow through the bottles was 1.0 nL/min and a calibrated gas volume meter was used to measure the total sampled volume. High Performance Ion Chromatography (HPIC) was used for the analysis of the absorption solutions. The sample gas was continuously extracted from the centre of the exhaust duct during the full test time. After the test the sampling tube was rinsed to collect any HF deposited inside the tube in order to minimize any losses of HF for the analysis.

RESULTS AND DISCUSSION

Figure 2 shows HRR and HF mass flow for the K2 cells (test A and B). The fully charged cell shows higher HRR peaks, similar to the results in Larsson et. al. [1], also the case with 50% SOC shows some peaks in contradiction to how the 50% SOC pouch cells behaved in Larsson et. al. [1]. This is probably due to that cylindrical cells can withstand more pressure before the safety valve releases the gas. The HF gas emission peaks are higher for 100% than for 50% SOC. However, the K2 50% test was the first run in the test series and it has later proved that the measurement systems, e.g. the FTIR sampling system (tubes and secondary filter etc) is catching HF before it gets saturated on HF. It is thus difficult to make a direct comparison between the 50% and 100% SOC tests in this case, as a part of the released HF was saturated in the FTIR sampling, and lower HF values are therefore measured for K2 50%. It could also be noted that the test with K2 50% SOC was run about one year later than the one with 100% SOC. About nine “sound bangs” were heard for the test B with 50% SOC, corresponding to cell opening (e.g. safety vent) in each K2 cell while eight “sound bangs” were heard for the test A with 100% SOC, suggesting that one K2 cell did open in some other way, e.g. a softer/earlier safety vent opening, or that two cells opened at the same time.

Figure 3 shows HRR and HF gas emissions for test C. In the test, one of the five cylindrical Lifetech cells exploded and the cell interior was expelled [3]. The reason for this was that the safety vent did not open, and this happening elucidate that the safety mechanics (in this case, the safety vent) can malfunction. Figure 4 shows the results for test D. The center temperature between the two cells reaches about 600 °C. The production of HF is about 2 minutes delayed after the HRR, similar to test A-C. The cell voltage breakdown in the bottom cell occurs at the same time as HF gas emissions and cell temperature increases rapidly, suggesting the occurrence of thermal runaway starting in the bottom cell. The cell voltage of the top cell breaks down about 1 minute later. The battery cells burnt...
relatively fast (i.e. giving high HRR).

![Graph](image1.png)  
**Figure 2**  Results for K2, test A 100% SOC (left) and test B 50% SOC (right). The “1 min average” is calculated by 5 points moving average of each 12 seconds spectrum.

![Image](image2.png)  
**Figure 3**  Results for test C, Lifetech 100% SOC. The photo is taken during tear-down analysis and showing the cell interior expelled out. The cell was caught by the steel net in the protective test box.

![Graph](image3.png)  
**Figure 4**  Results for test D. The photo is taken from the long side, after the test is complete.

The detection limit for HF for the equipment used in this investigation is 2 ppm [1]. The peak ppm levels for the tests in Figures 2-4 are 9 ppm (test A), 5 ppm (test B), 16 ppm (test C) and 100 ppm (test D), all well above the detection limit. Detailed results for the tests are shown in Table 2. The weight loss of the battery cells was between 19 and 25%. The total amounts of HF gas emissions were between 12 and 81 mg/Wh and 7 and 27 mg/g (where g corresponds to the weight loss). The secondary measurement with gas-washing bottle technique in test D, gave about twice the amount of HF, however still in the same order or magnitude as the FTIR measurement.
An electrified vehicle today could have a battery pack ranging between 10-90 kWh. Battery packs in heavy-duty electrified vehicles (buses, trucks, etc.), in ships and in stationary electrical grid could have significantly larger battery systems. Extrapolating for a worst case scenario of a 100 kWh battery pack (e.g. 400 VDC, 250 Ah), the amount of released HF could be 1200-8000 g. The IDLH (Immediately Dangerous to Life or Health) value for HF is 0.025 g/m³ [4]. If the HF gas emissions would be homogeneously distributed this amount of HF has to be diluted in more than 50 000 - 300 000 m³ of air not to exceed the IDLH value. This volume corresponds e.g. to a total fire in an electric vehicle with 100 kWh battery pack parked in a 15000 – 100000 m² garage of 3 m in height. Another example of a larger 1 MWh battery pack in e.g. a stationary storage in an apartment-complex would result in a volume corresponding to about 1500 – 10000 apartments of 300 m³ each (e.g. 100 m² with 3 m in height). These examples assume that the gases are not vented away but stay in the building. However, it is important to note that all fires produce smoke and one should also for that reason not stay within the room/building if there is a fire going on.

Table 2. Detailed results of HRR, total heat release (THR, integrated HRR) and HF gas emission release. The energy capacity in Wh is calculated by nominal voltage times nominal capacity.

<table>
<thead>
<tr>
<th>Test</th>
<th>Weight loss (g, %)</th>
<th>Max HRR (kW)</th>
<th>THR (kJ)</th>
<th>Hydrogen fluoride</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>145 g 19.7 %</td>
<td>29</td>
<td>2766</td>
<td>1.2 1.0 2.2 N/A 15 24</td>
</tr>
<tr>
<td>B</td>
<td>155 g 21.0 %</td>
<td>19</td>
<td>2502</td>
<td>0.7 0.4 1.1 N/A 7 12</td>
</tr>
<tr>
<td>C</td>
<td>406 g 24.6%</td>
<td>31</td>
<td>6605</td>
<td>6.3 1.3 7.6 N/A 19 58</td>
</tr>
<tr>
<td>D</td>
<td>419 g 19.1%</td>
<td>53</td>
<td>6893</td>
<td>4.8 1.6 6.4 11.2 15-27 46-81</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The total amounts of HF gas emissions measured in these tests on commercial Li-ion cells were 12-81 mg/Wh for the different batteries tested. The HF release for a large battery pack exposed to fire could thus in a worst case scenario result in a very large volume of toxic gases.

ACKNOWLEDGEMENTS

The Swedish Energy Agency, the Swedish Fire Research Board and Carl Tryggers Stiftelse för Vetenskaplig Forskning are greatly acknowledged for their support. Several technical staff colleagues at SP Safety have contributed to this work.

REFERENCES

4. Documentation for Immediately Dangerous to Life or Health Concentrations (IDLHs) for Hydrogen Fluoride (As F); The National Institute for Occupational Safety and Health (NOISH): Washington, DC, USA, 1994.
KISS the Fire

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KISS THE FIRE

Some kiss their partner goodbye, some kiss their lover goodbye, some even kiss both goodbye but can you really Kiss a fire goodbye?

Unfortunately, probably not but the phrase “KISS” does help us to understand how to design systems that have the best chance of extinguishing a fire.

The acronym KISS has many meanings including “keep it simple, stupid and keep it simple straight forward” but the fundamental meaning is the same. Don’t over complicate a design and most importantly keep what can go wrong to an absolute minimum.

Ironically it was a man of Swedish descendant who has been credited with this phrase (Kelly Johnson) and whether or not it was just a coincidence he was working with Americans at the time remains a mystery!

Figure 1 Kelly Johnson (Aircraft engineer)

What Kelly realised was despite designing some of the most innovative and complex aircraft in the world you must never lose sight of fundamentals of the specification. For him this was to fly man faster and safer than ever before but for fire engineers the fundaments are even simpler, “put the fire out”!

Now of course there should not be a fire in the first place and if all the elements of vehicle design are correct then there won’t be.

Unfortunately, the complexities of modern vehicles and the multitude of fuel & energy sources utilised do make it very difficult to mitigate the risk of fire so how do we as fire suppression designers combat this?

Well as you have no doubt seen this week there are many methods of suppression available with a wide variety of detection technology and a huge choice of extinguishants. From all these systems is there really one that is suitable for all vehicles??

Vehicles (especially buses) vary in design from region to region and whilst some have large ventilated risk areas, others have small compartmentalised spaces.
Some are powered by natural gas or LPG. We have ethanol or diesel vehicles. Then there are those that use electricity with various types of batteries. There are even vehicles that use a Hybrid of these fuels.

If we initially look simply at the extinguishant choice then we already have a dilemma as the fuels cover almost the complete recognised range of Fire classes, and whilst one agent may be the primary solution for one hazard it may be secondary or even tertiary for another. In fact, in some cases, an extinguishant that is perfectly suited to one fuel source of a Hybrid vehicle may actually be totally incompatible with another!

![Figure 2 Fire Classes](image)

Then if we look at the detection methods we have another dilemma. Is the detector that works well in a large ventilated area the same one that performs well in smaller multi compartments, some of which are at higher temperatures?

Vehicle has a very large ventilated engine area and is fully open at the bottom. Extinguishant will need to cover large area.

Vehicle has a compact engine space with minimal ventilation. Ambient temperature will be very high and any extinguishant release will be very close to engine.
Finally, there is the principal of operation that we choose for the Fire suppression system. As designers we need to consider another acronym “FMEA”. This is the failure mode effects analysis and what it means is we have to look at our design and ascertain what can go wrong and what happens if it does? Now some of the outcomes are insignificant but a number can mean a failure to operate correctly and ultimately this could mean we do not achieve our aim. In our case THE FIRE IS NOT EXTINGUISHED!

Verification & validation is key to minimizing any potential failures and this can include undertaking various product approvals. In the case of fire suppression testing it is important to try and simulate the perceived scenarios and come up with a method that is repeatable for analysis. It is also important to include all elements of the systems performance. Too often testing prioritises the performance of the extinguishant medium without giving enough consideration to the detection methods. The two are in inextricably linked and a good detector with a poor extinguishant can be just as effective, or ineffective as a great extinguishant with a very poor detector!

So how do we minimise the risk of failure? Well this is where KISS comes back in. In order to reduce the potential to fail you have to go back to basics, and keeping the system as simple or stupid as possible could hold the key.

If you can minimise the reliance on external influences like power supplies or separate detectors, then this makes the system more autonomous and reduces the potential to fail.

If you can reduce the amount of moving parts and seals, then again this reduces opportunities to fail. In fact, if the principal of operation is simple then it can practically become almost fail safe. Furthermore, if you can monitor all the key components then this should lead to notification way prior to potential failure.
In summary if you can design a fire suppression system that does not require power, has no moving parts, relies on no reactions and can have the key components constantly monitored then perhaps it is feasible to rule out operational failures.

That just leaves us with performance. Can any of the current fire suppression systems guarantee to extinguish all foreseeable fire scenarios?
If the answer is yes, then maybe it justifies the most complicated, expensive systems and the failure risks associated with them.
If the answer is no, then maybe it’s time to reconsider the simple approach and ensure that the system reliably operates and reliably notifies those at risk.
For passenger vehicles we must place great emphasis on the safety of those on board and early notification / evacuation can be the key difference when dealing with a thermal incident.

By keeping it simple we can ensure that the right extinguishant is used for the right application.

Maybe we can stop looking for a one size fits all solution and accept that the risks vary so widely on vehicles that no one system or one extinguishant will ever suit them all.

Perhaps we can even accept that one approval may not match all the variations and look to develop standards for specific fuel & vehicle types.

Maybe the vehicle designers can one day design out the risk of fire.

Until that day then we will need to continue to design and develop fire suppression systems to combat the ever present risk of fire and maybe by going back to basics and ensuring we don’t ignore the fundamentals of fire engineering then one day we really will KISS the fire goodbye.
INTRODUCTION

This paper documents a study analyzing motorcoach and school bus fire safety performed by the Volpe National Transportation Systems Center (Volpe) for the U.S. Department of Transportation (USDOT), Federal Motor Carrier Safety Administration (FMCSA), Technology Division, Office of Analysis, Research, and Technology. The objective of this study is to identify the causes, frequency, and severity of motorcoach and school bus fires in the United States, and determine potential ways to prevent or reduce the severity of these incidents, especially through improving the effectiveness of vehicle inspection practices. This study succeeds the 2009 Motorcoach Fire Safety Analysis [1] (henceforth referred to as the 2009 study), which was also presented at the 2012 FIVE Conference [2], and has been expanded to include school bus fires.

The 2009 study established a database of spontaneous motorcoach fire records from U.S. government, industry, and media sources, and analyzed the safety risk of motorcoach fires. The study also sought to identify potential measures for risk reduction. The 2009 study found that engine and wheel area fires accounted for almost 70 percent of all fires. The most frequently identified points of ignition were brakes, turbochargers, tires, electrical systems, and wheel/hub bearings; 95 percent of all reported fires resulted in no direct injuries or fatalities.

The current study updates and expands on the 2009 study to include all motorcoach fires (i.e., spontaneous, intentional, or the result of a collision or rollover) that occurred from 2004 to 2013. In addition, the report evaluates school bus fire risk, estimates the impacts of recent technology changes on motorcoaches and school buses, and expands on the evaluation of the effectiveness of automatic fire detection and suppression systems.

DATA SOURCES

Although there are credible estimates of the frequency of fires on all types of buses combined, motorcoach- and school bus-specific estimates are not easily found in State and Federal accident statistics, national fire databases, and general media sources.

Primary data sources for this study were the U.S. Fire Administration’s (USFA) National Fire Incident Reporting System (NFIRS) and FMCSA’s Motor Carrier Management Information System (MCMIS). Other supplemental sources included insurance and media records, the National Highway Traffic Safety Administration’s (NHTSA) State Data System (SDS) for selected States, and the Federal Highway Administration’s (FHWA) Highway Statistics. Motorcoach and school bus population and characteristics data were obtained from R.L. Polk and Co.

The analysis in this study required more reliance on the incident data from Federal sources and from R.L. Polk than on the secondary sources in comparison with the more extensive coverage of all sources in the 2009 study.
KEY FINDINGS

- School bus fires reportedly occur more frequently than motorcoach fires. On average, motorcoach fires in the United States occur slightly less than daily, while school bus fires occur slightly more than daily. The frequency trend for both motorcoach fires and school bus fires from 2004 to 2013 is similar, with a general downward trend over the 10-year period. (See Figure 1.)

![Figure 1](image)

- Deaths and injuries as a result of a motorcoach or school bus fire are rare, but can be severe in worst-case scenarios. The vast majority of the reported fires resulted in no direct injuries or fatalities, and the average reported property damage per incident was a fraction of the total cost of the vehicle.

- The ratio of motorcoach fires to billion highway vehicle miles traveled (VMT) is highest in the Eastern and Southern regions compared to Midwestern and Western regions of the United States. The greatest number of school bus fires occurred in the Southern and Midwestern regions, compared to the Western and Eastern regions.

- The most frequent cause of ignition was failure of equipment or heat source for both motorcoaches and school buses. Unlike motorcoach fires, a significant number of school bus fires were classified as intentional.

- The most frequent area of origin for motorcoach and school bus fires was the engine area, running gear, or wheel area. Seventy-seven percent of motorcoach fires and 68 percent of school bus fires with known areas of origin originated in these areas. A significant number of these fires on motorcoaches cited a tire as the item first ignited, and are likely wheel area fires. A significant number of engine area, running gear, or wheel area fires on school buses cited electrical wire as the item first ignited and are likely electrical fires.

- The most frequent contributing factor for both motorcoaches and school buses was mechanical failure or malfunction, followed by electrical failure or malfunction. However, motorcoach fires are more likely to be mechanical in nature than electrical compared to school bus fires. (See Figure 2.)

- About 50 percent of the motorcoach fire incident records involve vehicles of model year 1998 to 2003. These motorcoaches not only had a higher reported frequency of fire occurrences but also had a substantially higher reported incident rate relative to their population. School bus
fire records by model year were more evenly distributed than motorcoach fire records, but also had a period of higher frequency for model years 1996 to 2001. (See Figure 3.)

- An analysis of vehicle age showed that the percent of newer vehicles that caught fire in 2005 was higher than the percent of newer vehicles that caught fire in 2009 or 2013, indicating that implementation of advanced technologies such as fire suppression systems may have a positive effect on fire prevention and mitigation of reportable fires. (See Figure 4.)

![Motorcoach and school bus fires 2004-2013, by factor contributing to ignition.](image)

![Fires and vehicle population by model year.](image)
Much like the 2009 study, this analysis showed that vehicle out-of-service (OOS) rates for motorcoaches involved in a fire are generally higher than OOS rates for all buses inspected, and this difference appears to be increasing. The OOS rate for fire-involved motorcoaches from 2005 to 2009 increased each year from the level of all buses to the level of all commercial motor vehicles (CMVs), indicating that the OOS rate may prove to be a reliable indicator of fire risk.

For carrier safety ratings following investigations, motorcoach carriers involved in fires have a higher rate of operational or vehicle-related compliance problems than those without fire involvement, indicating that a less-than-satisfactory safety rating could be an indicator for fire risk.

The FMCSA monitors motor carriers for ongoing safety problems, and prioritizes them for intervention, based on their compliance with safety regulations, as measured according to Behavior Analysis and Safety Improvement Categories (BASICs). Motorcoach carriers involved in fires are more likely to have exceeded the safety Intervention Threshold in the Vehicle Maintenance BASIC than those without fire involvement, suggesting that high percentiles in the Vehicle Maintenance BASIC may serve as a predictor of increased fire involvement.

REFERENCE LIST


KEYWORDS:
Post-Collision Fires in Road Vehicles, a Pre-Study

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INTRODUCTION

The loss of human lives and body injuries as a consequence of post-crash fires either by smoke inhalation or due to burn injuries are not uncommon. For instance, a study published by Viklund et al [1] shows that 5% of all fatalities in Swedish roads due to collisions in passenger cars, sport utility vehicles, vans and minibuses which took place between 1998 and 2008 occurred in burning vehicles. It is interesting to notice that the aforementioned statistics have the same proportions than other countries, such as in the U.S.A. where, on average, 31 vehicle fires are reported per hour and these are responsible for around 300 deaths and 800 injured persons per year. Furthermore, these vehicular fires are responsible for 12% of deaths, 8% of civilian injuries and 9% of the direct property damage attributable to all the reported fires. For the case of Sweden, the cause of death in one third of the reported incidents was attributable to fire only with no or limited trauma injuries. This means that in these cases the occupants did not die due to the combined effect of trauma and fire injuries, but for the effect of fire only.

The vast majority of fire deaths are caused by smoke inhalation and not by burns as it is popularly believed. Smoke incapacitates the occupants of a vehicle fast enough to impede their evacuation from the burning object before the fire spreads and totally engulfs it. Fire can incapacitate or kill by reducing oxygen levels, either by consuming the oxygen, or by displacing it with other gaseous effluents. Even non-poisonous gases can be deadly when hot since these can cause burns in the respiratory tract.

The large amount of fatalities following vehicle fires can be understood by the low fire performance of the materials used for vehicle manufacturing. Although there is a legislation specifying some minimum requirements with regard to fire performance of materials fitted in vehicles, the existing legislation is flaccid when compared to the fire safety regulations for the aeronautic, marine and rolling-stock sectors. For example, fire prevention requirements in buses, do not cover aspects such as the limitation of peak heat release rate, smoke yield and toxicity as done in regulations for trains, planes and ships.

Reducing fires in vehicles is strongly related to the survivability of the occupants against a collision event. Statistics show that occupants travelling on modern vehicles have higher probabilities of surviving to a severe impact than of those travelling on vehicles with older technologies. This is however expected, the active and passive safety systems increase the survivability rate but these do not reduce the risks of a fire as a post-collision event.

In order to reduce the number of injuries and human fatalities associated to post-crash fires in road vehicles, it is necessary to study the causes of these lethal fires. Of particular interest are the ignition sources, vehicle types, fire dynamics and toxicology mechanisms which directly contribute to the loss of human lives, for instance, the dynamics and toxicity of fires due to upholstery and materials in passenger compartments or toxic gases due to fires in electric vehicles. New materials and traction systems (e-vehicles) introduces new toxic substances when burning – but intoxication by some of
them could be reduced by using available antidotes – which make knowledge of these substances necessary.

RESULTS

Even though car fires due to collisions are relatively rare, they play an important role when it comes to fatalities and should be studied thoroughly so as to lower this fire risk. Taking a closer look to the FARS database, all categories of vehicles do not have the same probabilities of catching fire. Passenger cars and light trucks have similar rates, ranging around an average of 3%, the rates of passenger cars slowly increasing over the years, the one of the light trucks being more stable. Large trucks have a much higher rate, varying between 5 and 7%. The amount of large trucks involved in these accidents are however much smaller than passenger cars and light trucks, which could be an explaining factor of the higher variability of the data over the years. It would be interesting to determine the leading mechanisms behind the higher fire rate for large trucks. Hazardous loads could play a role, as well as the extra fuel tanks built in these vehicles. Interesting to note is that the rate of fatalities occurring in burning vehicles is slightly higher for light truck vehicles (average of 5.2% for 2002-2014) than for passenger cars (4.6%), while it is much higher for heavy trucks (20.5%). This is due to the fact that heavy truck passengers rarely die in fatal crashes compared to the occupants of the other vehicle involved, unless there is a fire entry. As heavy trucks were not the main point of interest of this study, this question was not analysed any further, but would be of interest for later research.

Zooming in on the passenger cars and their increasing fire rates but focusing on the model years, no major difference could be seen between the car pool aged 0-4 and the one aged 6-10 with the FARS data shown in Figure 1. This would indicate that newer models do not per se lower the fire risk on the basis of this data, and that even though they generally speaking seem to have a better behaviour during the period 2009-2011, their fire rates have caught up again the ones of the 6-10 years in 2012. Interestingly, Digges [2, 3] notes that the fire threat has increased for passenger vehicles in recent model years, specifically when it comes to frontal crashes and rollovers. In Digges is stated that the combustible material has increased 10-fold in the last decades. The increase and change of properties of the combustible material has transformed the fire threat.

Figure 1  Fire rate of passenger cars, according to age category. FARS data, 2002-2014. This graph reflects the fire rate of passenger cars of a certain age category involved in fatal crashes. In blue: models aged 0 to 4 years, in orange models aged 6 to 10 years.
CONCLUSIONS

This study indicates that fire events related to post-collision events are a significant problem. The increased combustible load in newer vehicles is an important factor to be taken into account for the fire safety, as well as their potential to release toxic fumes while burning.

Trends indicate that the survivable collision energy will continue to increase and, at the same time, the probability of post-crash fires rises with the collision energy. This means that the occupants of a vehicle will probably survive a high energy collision but will sustain severe injuries or death due to a post collision fire.

Indeed, as crashes are expected to become more survivable with advanced technology, fire events might become even more relevant. Database analysis gives an interesting general picture of the situation, but unfortunately the difficulty of analysing these fire events more precisely, the lack of reporting and thus high proportion of unknowns are obstacles to an in-depth analysis. Different reporting methods between the databases and between countries make it difficult to compare the data on an equal basis. The determination of causal factors is also a challenge as so many variables need to be taken into account.

The fire situation of a car is complex, involving many combustible materials, and which proceeds rapidly with smoke generation. The role of individual polymers can have some impact on the first phases in a fire situation, and therefore the use of flame retardants in these polymers is important to give extra time for evacuation of passengers. During later phases it is likely that the fire will proceed very rapidly, and polymer selection will not have a greater role in the fire behaviour.

Polymers will become more and more important in car components due to their low weight, easy processability and good properties. In a fire situation in a car, all polymers will pose a potential health risk. As polymers are crude oil based organic materials they can act as fuel in a fire, which and further their decomposition will case the formation of hazardous gases and decomposition products. However, the fire retardancy of polymers can rather easily be improved by using flame retardants. Many flame retardants are toxic or problematic from the environmental point of view, but today many more environmentally benign flame retardant systems are under development, and will be introduced into the market.

The decomposition of polymers will form very hazardous gases and products. Chlorine in PVC will form HCl, while nitrogen containing polymers (polyurethanes and polyamides) will form HCN. Unfortunately these polymers have very good properties suitable for car components, so it is unlikely that these can be replaced by other polymers.

Few studies have been able to directly study the impact of car fires to the environment. Emitted toxic species have been largely reported for air, water and soil systems and could represent in some cases an important share of the pollution load of Sweden, such as for PAHs and PCDDs/PCDFs. Even though most car fires will present local and minor pollution events, specific situations in sensitive areas could lead to more serious consequences. Containment and appropriate treatment of the suppression medium are therefore important.

To some of the most toxic gases as HCN and HF the emergency service may have a possibility to use specific antidotes at an early stage to reduce the consequences – in combination with usual methods with oxygen therapy etc. given that they have knowledge about expected gases.
REFERENCES

Discrimination of Short-Circuit Molten Marks on Steel Plates and Electrical Wiring in Determining Cause of Automobile Fires

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ABSTRACT
Molten marks in wiring are often used by investigators to determine the cause of an automobile fire. However, it is difficult to determine whether these molten marks were caused by electrical failures or by the fire itself. In this paper, the molten marks in short circuits between electrical wiring and steel plates were evaluated by observing their appearance and metallographic structure. We found that it is difficult to determine whether the molten marks on the wires were caused by electrical failures or the fire. However, the molten marks on the steel plates exhibited differences between the marks caused by electrical failures and those caused by fire.

KEYWORDS: Fire investigation, electrical failure, molten marks

INTRODUCTION
After an automobile fire, molten marks are sometimes left on the wiring of the vehicle. Such molten marks are an important clue in determining the cause of fires induced by electrical failures. However, as molten marks can be caused either by electrical failure (referred to as “primary molten marks”) or by the fire itself (referred to as “secondary molten marks”), it is necessary to determine whether the molten marks are of the former or latter type in order to identify the cause of the fire. Investigators have suggested several methodologies for determining the types of molten marks, including observation of the appearance and metallographic structure as well as performing an elementary analysis by Auger Electron Spectroscopy (AES) of molten marks generated on the wiring side. In crash accidents, short circuits may sometimes occur between steel plates and electrical wiring as the car body is utilized as a ground by the electrical circuits. In automobile fires, molten marks can be formed not only on wires but also on steel plates, as indicated in Figure 1.

The type of a molten mark can be determined by observing its appearance, including the shape, glossiness, and smoothness of the surface. Table 1 lists the characteristics of primary and secondary molten marks, as reported by Ishibashi et al. They reported that primary molten marks tend to have a hemispheric shape, to be glossy, and to have a smooth surface.

Figure 1 Molten marks formed on the car body (from a crash vehicle fire).
### Table 1  Discrimination by surface inspection

<table>
<thead>
<tr>
<th>Molten marks</th>
<th>Shape</th>
<th>Gloss</th>
<th>Smoothness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Hemispheric</td>
<td>Glossy</td>
<td>Smooth</td>
</tr>
<tr>
<td>Secondary</td>
<td>Misshape</td>
<td>Lose its gloss</td>
<td>Rough</td>
</tr>
</tbody>
</table>

The types of molten marks can be determined by observing the cross-sectional metallographic structure, including the distribution of empty space (voids), the involvement of foreign substances and the size of the crystals. If the period from molten state to solid state is short, i.e. if the molten marks are formed at a fast cooling speed, there will be fewer voids and the crystals will tend to be small. Therefore, primary molten marks tend to have smaller crystals with fewer voids compared with secondary molten marks produced by a nearby flame. Based on this tendency, the types of molten marks can be discriminated.

In this paper, the molten marks in short-circuits between electrical wiring and steel plates were evaluated by observing their appearance and the metallographic structure. Based on these results, we will propose how to discriminate primary molten marks from secondary ones.

#### TEST METHOD

We made samples of primary and secondary molten marks with the following six processes, using cables for automobile, AVS2.0 (Nominal sectional area: 2.0 mm², permissible current: 19 Ampere).

**How to make samples of primary molten marks**

Process #1: We peeled 10 mm of insulation from the edge of an automobile wire (designated as L in Figure 2 and placed it in contact with a steel plate. Power was supplied by a battery used for automobiles. An electric current of approximately 600 A flowed through the short circuit.

**How to make samples of secondary molten marks**

Process #2: We made contact in the same configuration as Figure 2, with the wire and the steel plate exposed to a propane-air diffusion flame for 1 minute.

#### RESULTS AND DISCUSSION

Both the primary molten mark formed without flame (Process #1, figure 3) and the secondary molten mark formed in the same configuration in the presence of a flame (Process #2, figure 4) had a hemispheric shape. There was no remarkable difference in the number of voids in the inner structure.
or in the particle size of the crystals. These results indicate that it is difficult to discriminate primary and secondary molten marks by observing the burnt portion and cross-sectional metallographic structure of molten marks in wiring sides. However, in addition to molten marks on the wiring side, we studied those on the steel plate (molten marks in plate sides). Figures 5 and 6 illustrate the burnt cable (on the right) and the cross-sectional metallographic structure (on the left) of the molten marks in plate sides, formed by the respective processes #1 and #2.

**Figure 3** Appearance and cross-sectional metallographic structure of a primary molten mark on the wiring side.

**Figure 4** Appearance and cross-sectional metallographic structure of a secondary molten mark formed on the wiring side.

**Figure 5** Appearance and cross-sectional metallographic structure of a primary molten mark formed by process #1 on the plate side.

**Figure 6** Appearance and cross-sectional metallographic structure of a secondary molten mark formed by process #4 on the plate side.

The primary molten mark had a small amount of molten metal in the area of contact with the steel plate, with no wetting and spreading of the molten metal. In contrast, the secondary molten mark had a large amount of molten metal with wetting and spreading. Further, the primary molten mark on the plate side tended to retain the original form of the wire strand. Observation of the metallographic
structure demonstrated that the sizes of the crystals in the primary molten mark tended to be heterogeneous while those in the secondary molten mark tended to be homogenous. The reasons are as follows.

We measured the surface temperature of the molten marks during their forming process using an infrared thermal image.

Figure 7 demonstrates the surface temperature of the molten marks formed on the wiring and the plate 0.2 seconds after the snapping of the wire. Figure 8 illustrates the average surface temperature of the areas (a) on the wiring or (b) on the plate as indicated in Figure 7. Since it is difficult to measure the surface temperature if a flame exists or if the diameter of the wire is very small, a coating-free wire with a sectional area of 3.14 mm² was placed in contact with a steel plate for this experiment. The emissivity was set at 1.0.

The heat capacity of the steel plate is very big in comparison with that of the wiring copper. Therefore, cooling of the primary molten marks on plate side starts immediately after the wire is snapped into a wiring side and a plate side by a short circuit between the wiring and the plate. However, the cooling rate of a secondary molten mark on plate side shorted on a heated steel plate by fire, is slower than the primary molten marks. Based on these results, we conclude that molten marks on the plate side are more informative than those on the wiring side for discriminating primary and secondary molten marks by observing their appearance and cross-sectional metallographic structure.

CONCLUSIONS

In the present study, we evaluated primary and secondary molten marks formed by short circuits between automobile wiring and a steel plate by observing the mark appearance and metallographic structure. As the result, molten marks can be distinguished by observing them and the cross-sectional metallographic structure of marks on the plate. The visual inspection should include checking the wetting and spreading of molten metal as well as the existence of wire strands on the plate.

REFERENCES
