ABSTRACT

This report includes the Proceedings of the 2nd International Conference on Fires in Vehicles – FIVE held in Chicago September 27-28, 2012. The Proceedings includes 20 papers given by session speakers and 14 papers presenting posters exhibited at the Symposium. The papers were presented in 6 different sessions. Among them are Incident and Case studies, Fire Statistics, Fire development, Alternative fuels, Regulations and standards and Detection and suppression. In addition was each day opened by two invited Keynote Speakers addressing broad topics of interest.

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PREFACE

These proceedings include papers from the 2nd International Conference on Fires in Vehicles – FIVE held in Chicago September 27-28, 2012. These proceedings include an overview of research and regulatory actions coupled to state-of-art knowledge on fire related issues in passenger cars, buses, coaches, and trains.

Fires in transport systems are a challenge for fire experts. Rapid developments in lightweight materials make it possible to build ships, high-speed trains, metro trains, buses and other vehicles with improved fuel economy, able to carry more load per litre of fuel, and thus with reduced environmental impact. New fuels that are efficient and environmentally friendly are rapidly being introduced together with sophisticated new technology. This rapid development, however, introduces new fire risks not considered previously and we risk a situation where we do not have sufficient knowledge concerning to tackle them. In this context FIVE represents an important forum for discussion and 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. This means that our understanding of safety and regulations must be developed internationally and in that context the FIVE-conference has a significant role to play as a place to exchange knowledge.

We are very proud to have established FIVE which attracts high attendance of experts, researches, 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 incident and case studies, on fire statistics, on fire development in vehicles, on alternative fuels, on detection and suppression and on regulations and standards. We are grateful to the renowned researchers and engineers presenting their work and to the keynote lectures that were setting the scene.

I would also like to take this opportunity to thank our event partner Fire Protection Research Foundation for the co-operation and invaluable help in reviewing papers and helping to realize this conference in Chicago.

Björn Sundström

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 Fire Technology.
# TABLE OF CONTENTS

## KEYNOTE SPEAKERS

- **Bus Fires in the United States: Statistics, Causes and Prevention**  
  Robert A. Crescenzo, Lancer Insurance Company, USA  
  [9]

- **Historical Fires and their Impact on Regulations and Research**  
  Petra Andersson and Björn Sundström, SP Technical Research Institute of Sweden, Sweden  
  [17]

- **Fire Protection Strategies for Lithium Ion Batteries: a Status Update from the Fire Protection Research Foundation**  
  Kathleen H. Almand, Fire Protection Research Foundation, USA  
  [29]

- **Fire Suppression Systems in Buses and Coaches – How, Where and Why**  
  Joseph (Joey) Peoples, Kidde Technologies, USA  
  [37]

## INCIDENT AND CASE STUDIES

- **Motorcoach Fire Investigation and Wheel Well Fire Testing**  
  Joseph Panagiotou, National Transportation Safety Board, USA  
  [47]

- **Motorcoach Tire Fires – Passenger Compartment Penetration, Tenability, Mitigation, and Material Performance**  
  Erik L. Johnsson & Jiann C. Yang, National Institute of Standards and Technology, USA  
  [59]

- **Examples of Bus Fire Investigations**  
  Dieter Wolpert & Markus Egelhaaf, DEKRA Automobil GmbH, Germany  
  [71]

- **Commercial Vehicle Fire, Cause and Origin Analysis**  
  Christopher W. Ferrone, Americoach Systems, Inc., USA  
  [83]

## FIRE STATISTICS

- **Automobile Fires in the U.S.: 2006-2010 Estimates**  
  Marty Ahrens, National Fire Protection Association, USA  
  [95]

- **Bus Fires in 2010-2011 in Finland**  
  Esa Kokki, Emergency Services College, Finland  
  [105]

- **Motorcoach Fire Safety Analysis: The Causes, Frequency, and Severity of Motorcoach Fires in the United States**  
  Neil R. Meltzer, Gregory Ayres & Minh Truong, John A. Volpe National Transportation Systems Center, USA  
  [111]

- **Risk of Commercial Truck Fires in the United States: An Exploratory Data Analysis**  
  Jonathan Pearlman & Neil Meltzer, John A. Volpe National Transportation Systems Center, USA  
  [123]
FIRE DEVELOPMENT

Methodology of Fire Growth and Toxic Gases Production Simulation - Application to an European Train Vehicle
A. Camillo, T. Rogaumeb, E. Guillaumea, D. Marquisa, Laboratoire National de Métrologie et d’Essais (LNE), France

Fire Safety Performance of Buses
Anja Hofmann & Steffen Dülsen, BAM Federal Institute for Materials Research and Testing, Germany

Model Scale Metro Carriage Fire Tests – Influence of Material and Fire Load
Anders Lönnermark, Johan Lindström, Ying Zhen Li, SP Technical Research Institute of Sweden, Sweden

Quantification of Rapid Transit Vehicle Design Fire Heat Release Rates
James McBryde, Andrew Coles and Keith Calder, Sereca Fire Consulting Ltd, Canada
Harold Locke, Locke & Locke Inc., Canada

ALTERNATIVE FUELS

Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.
Amandine Lecocq, Marie Bertana, Benjamin Truchot and Guy Marlair, INERIS – National Institute of Industrial Environment and Risks, France

Comparison of Fire Behaviors of an Electric-Battery-Powered Vehicle and Gasoline-Powered Vehicle in a Real-Scale Fire Test
Norimichi Watanabe, National Research Institute of Police Science, Japan,
Osami Sugawa, Tokyo University of Science, Japan,
Tadahiro Suwa, Saitama Prefecture Police, Japan,
Yoshio Ogawa, National Research Institute of Fire and Disaster, Japan,
Muneyuki Hiramatsu, Hino Tomonori, Hiroki Miyamoto, Katsuhiro Okamoto and Masakatsu Honma, National Research Institute of Police Science, Japan

National Electric/Hybrid Vehicle Training Programs for First Responders
Andrew H. Klock, National Fire Protection Association, USA

Determining Hydrogen Concentration in a Vehicle after a Collision Test
Yohsuke Tamura, Noriaki Ohtsuka, Masayuki Takeuchi and Hiroyuki Mitsuishi, Japan Automobile Research Institute, Japan

REGULATIONS AND STANDARDS

Comparison of the U.S. and European Approaches to Passenger Train Fire Safety
Stephanie H. Markos, John A. Volpe National Transportation Systems Center, USA
Melissa Shurland, Federal Railroad Administration, USA

Jonas Brandt and Michael Först, SP Technical Research Institute of Sweden, Sweden
DETECTION AND SUPPRESSION

The Cost Effectiveness of On-Board Train Fire Suppression Systems in Underground Rail Transit Systems
William D. Kennedy, Tora Fuster & John Swanson, Parsons Brinckerhoff, U.S.A.

A Comparison of Various Fire Detection Methodologies in Transit Vehicle Fire Protection Systems
Paul Smith & Adam Chattaway, Kidde Graviner Ltd, UK
Joseph (Joey) Peoples, Kidde Aerospace and Defense, USA

POSTERS

Developing a Fire Resistance Test for Vehicles with Rechargeable Energy Storage Systems
Petra Andersson and Magnus Bobert, SP Technical Research Institute of Sweden, Sweden

Extreme Duty Fire Products Improve Vehicle Protection.
Richard J Barone, TPR2 - Thermal Product Research, USA

Dr. Adrian Beard, Clariant Produkte (Deutschland) GmbH, Germany,
Jérôme De Boysère, Thor GmbH, Germany
Dr. Michael Klimes, Nabatlec AG, Germany

The Development of a Standard Test for Assessing the Effectiveness of Transit Vehicle Fire Extinguishing Systems
Adam Chattaway, Robert Dunster and Paul Weller, Kidde Graviner Ltd, UK
Joseph (Joey) Peoples, Kidde Aerospace & Defense, USA

Effectiveness of Shielding Vehicle Hot Surfaces
Cam J. Cope, Auto Fire & Safety Consultants, Inc., USA
John M. Stilson, Stilson Consulting, USA

Protecting Automotive Cooling Fan Modules from Damage Caused by Thermal Runaway
Faraz Hasan, TE Circuit Protection, USA

Fires in Rolling Stock – Testing and Validation
Michael Klinger & Stefan Krazmeir, IFAB – Institute for applied fire safety research, Germany

The Key to Suppression is Detection
Scott Starr & Angela Krcmar, Firetrace International, LLC., USA

Fire Safety Improvement of Vehicles
Susan D. Landry, Albemarle Corporation, USA

Energy Storage System Safety in Electrified Vehicles
Fredrik Larsson, SP Technical Research Institute of Sweden, Sweden and Chalmers University of Technology, Sweden
Bengt-Erik Mellander, Chalmers University of Technology, Sweden
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fire Protection Solutions for Road and Railway Vehicles.</td>
<td>307</td>
</tr>
<tr>
<td><em>Klas Nylander, Consilium Marine &amp; Safety, Sweden</em></td>
<td></td>
</tr>
<tr>
<td>Parking Brake Fires in Commercial Vehicles</td>
<td>311</td>
</tr>
<tr>
<td><em>Kerry D. Parrott &amp; Douglas R. Stahl, Stahl Engineering &amp; Failure Analysis, USA</em></td>
<td></td>
</tr>
<tr>
<td>Experimental Characterization of Automotive Materials in a Tunnel Fire</td>
<td>315</td>
</tr>
<tr>
<td><em>Xavier Ponticq, CETU, France</em></td>
<td></td>
</tr>
<tr>
<td>Shall We Consider New Design Fire Scenarios in Tunnel Fires Studies to Take Account of Fast Development of Electro Mobility?</td>
<td>319</td>
</tr>
<tr>
<td><em>Benjamin Truchot and Guy Marlair, INERIS, France</em></td>
<td></td>
</tr>
</tbody>
</table>
Bus Fires in the United States:
Statistics, Causes and Prevention

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ABSTRACT
The paper will review bus fire claims from three perspectives. The first will be a review of Lancer Insurance Company bus fire claim statistics from 2007-2011 including an emphasis on vehicle age, manufacturer, type of fire and impact of fire suppression systems. The second will be a review of the causes of these bus fire claims including mechanical/engine issues; wheelwell/bearing/brake issues and finally tire related fires. The third component of the paper will review prevention of bus fires by relating the claims statistics, the causes and issues including vehicle maintenance, driver training as well as the use of fire suppression systems. Statistics, causes and prevention will be supplemented by reviewing specific claims with an emphasis on formal causation studies and claim settlement outcomes.

Since 1985, Lancer has been the nation's leading provider of traditional liability, physical damage and general liability insurance coverages to the U.S. motorcoach and bus industries. The company provides onsite management and driver training, along with a wide range of free and exclusive safety and training products and services to policyholders companies of all sizes.

Bus fires and the resulting claims have been a serious concern over the last ten years. Unfortunately, the number of claims is rising in relation to the number of vehicles insured by Lancer Insurance Company. Additionally, the concern about passenger safety and the potential for serious injury makes these claims extremely important to understand.

KEYWORDS: bus fires, causes, prevention
PART I – THE PROBLEM

The threat of bus fires is a continuing concern for all operators. It seems that with every step forward and with all the technology available, there continues to be a significant number of bus fires in the United States.

The cost of a bus fire can devastate your company. Vehicle replacement, downtime and lost revenue, the risk to people and property and the public relations nightmare for your company, are just some of the consequences. Personal injury claims resulting from bus fires are rarely caused by burns; most injuries result from smoke inhalation and injuries sustained as passengers attempt to exit the vehicle through doors, windows or roof hatches.

Lancer Insurance Company, the largest insurer of buses in the United States, reviews its bus fire claims data on a regular basis. It is important to note, however, that our data only reflects bus fires reported to us by our policyholders. While there is other data from other organizations, most are not specific to charter/tour/passenger buses as is ours.

Our claims data since 2007, including charter, school and shuttle bus vehicle fires, reveal a total over 140 fires reported. Slightly more than 120 of those claims were just for charter/tour coaches, the rest were other bus vehicles. During that time frame, Lancer insured an average of 15,000 bus vehicles a year. The number of bus fire claims has risen at a higher percentage rate since 2007 in comparison to all bus fire claims prior to 2007. This is an alarming statistic.

These bus fire numbers represent about 1% of our total number of claims during that same five-year period, but represent over 6% of our claims costs. Lancer has spent nearly $11 million over the last 5 years settling bus fire claims. We have spent over $32 million settling bus fire claims since 1997! The average cost of settling a bus fire claim is over $80,000. It is important to point out that while bus fires represent only 1% of our claims frequency, they are equal in cost to much more common claims such as
sideswipe (the second most common claim), intersection and multi vehicle claims. The only types of claims that exceed the cost of bus fire claims are rear end accidents (the most common claim), ran off road (low in number but high in cost) and pedestrian hits (a very expensive claim). These comparisons point out that any one bus fire claim has the potential to significantly negatively impact a transportation company at any time. The thought that the cost of bus fire claims (without physical injury) can be higher than almost all other types of common claims is nothing short of alarming.

It is very important to note that very few of these claims involved personal injury costs, so the amounts cited are primarily for physical damage claims. Please remember: The entire vehicle universe we insure is not covered for physical damage. So, in essence, even these numbers do not reflect the actual number of bus fires at companies we insure because some policyholders decide against purchasing physical damage coverage. The actual numbers of bus fires in the US are higher than we know and their cost is certainly higher.

Bus fires remain a very serious issue for our industry and there appears to be little change on the horizon. The number of claims seems to fluctuate between 25-40 annually and are occasionally related to the age of the vehicle (both newer and older), but do not appear to reflect other economic issues, such as overall mileage driven, shorter trips or fewer passengers.
Regardless of the new options for fire suppression systems, tire pressure monitoring systems and other systems designed to prevent and/or fight fires, I am sorry to say we are making very little progress. No one system or approach will solve the problem. It is time for our industry to step up and really begin to take the problem seriously.

The argument that few people are seriously injured in bus fires is unacceptable. The Wilmer, Texas fire in September, 2005 has been carefully investigated and, not surprisingly, there were multiple contributing factors. That said, it must be remembered that 23 people tragically died in that bus fire. It can and will happen again, it is just a matter of time.

We can talk about prevention and the excellent work done in Sweden and other parts of Europe to create international standards, but unless the problem is seen as a global problem and a serious one at that, we are wasting our time.
PART II- CAUSES AND PREVENTION

To prevent fires, you must first know how and where they start. The two common places where the majority of motorcoach fires start are the engine compartment and tires/wheel wells.

1-The Engine Compartment

In the engine area, there are three main sources of fire. Often they combine to start a fire, but each can cause a fire independently as well. The first and most typical engine area fire source is from fuel leaks. Leaky hoses, loose fittings, seals that have gone bad or other problems in the fuel lines can allow fuel to leak. This leakage then seeps, or even drips, onto hot engine areas, resulting in fire. The second engine compartment fire source is an electrical short. Wires either become loose or get frayed by rubbing other wires or metal, creating electrical arcs that eventually ignite some other surrounding material. An engine that is dirty (i.e. covered with grease and oily substances from age or leakage) creates conditions ripe for fire that even just a small spark or high heat can start. Prevention “under the hood” requires a clean engine, quality maintenance and regular and close daily driver inspections. Newer vehicles are not immune from engine fires; they often run even hotter than older models and careful maintenance attention must be paid to turbochargers, heaters, and hoses.

Approximately 60% of all of our bus fires begin in the engine compartment and can be prevented by careful and systematic maintenance.

When talking about the engine compartment, the follow causes are also very important to discuss:

**Cause—Electrical or mechanical failure**

Grommet failure which causes wear of insulation on wires, and failure of other electrical components because of design or installation problems, are fairly typical examples of this fire starter.

**Prevention**

Solutions are tricky, because you often can’t see the area where a defect or misrepair might cause a fire. Here are a few tips that might help:

Pay careful attention to manufacturer maintenance recommendations and recall notices. When mechanics are fixing a manufacturer reported defect and encounter something they don’t understand, they should call the manufacturer—not guess at what should be done. Discourage, or better yet, prohibit improvised repairs.

When installing DVD players, TVs or any post-manufacturer equipment, carefully follow directions. Lancer’s data indicated that installers often rely on experience and memory and don’t take the time to read the accompanying technical information. If the specifications or installation process has changed, or if instructions were not properly followed, you have a potential problem.
Read maintenance manuals and strictly adhere to maintenance schedules. If your coach is involved in an accident, be aware of the potential for damage to hidden parts or components that are in electrical, mechanical or fire-sensitive areas. If necessary, perform a teardown to inspect them.

2-Tires/Wheel Wells
Underinflation of tires can create operating problems and expenses through poor tread wear, lower fuel mileage and, ultimately, the risk of a fire. While most tire fires start when dual wheels disguise a low air pressure problem, trouble can occur at any wheel position. Underinflated radial tires hold their shape and smooth operating characteristics down to very low air pressure. When tires are operated at low air pressure, heat builds up and a fire or shredding of the tire can result. To prevent a tire fire or a tire failure, check the tire inflation regularly. And beware: When dual tires are in service make sure to confirm the air pressure for each of the tires. That inside dual is the source of many a tire problem and resulting coach fire.

Wheel well fires related to brakes and wheel bearing failures are another serious cause of bus fires. Even a slight pull or drag on the brake can result in a fire.

Cause - Ride on flat tire and overheat
This is one of the most common fire claim types Lancer’s policyholders experience. There is just about an even split between cases in which the coach driver knew there was a flat but elected to keep going, and cases in which the flat tire was not easily detectable, usually because it involved an inner dual. It doesn’t take much time for a flat tire at highway speeds to heat to the point at which a fire ignites.

Prevention

Avoiding this type of fire begins with a careful examination of tire condition before vehicles leave the yard. An embedded nail or inadequate tread depth are warning signs. Your company must have a mindset that it will not, under any circumstances, operate vehicles if these conditions exist. If your decision is: “I’ll risk a flat tire to get the trip started on time,” you’re probably thinking the worst case would be a flat and a one-hour delay. Think again: The worst case would be a loss-of-control accident or a fire that causes injury or death to passengers and your driver, the loss of your coach…and probably your business.

Pre-trip inspections are essential to avoiding flat-tire fire losses. Do your drivers take the time to inspect the inner duals carefully? Ask yourself the tough question: Have we created an environment in which drivers care enough about the safety of our passengers and the protection of our equipment to go the extra step and perform that check?
Training on how to handle a flat tire is also critical. It is recommended that the driver stop as soon as safety permits, and inspect the tire and wheel well. If evidence of fire is detected, the passengers should be ordered to exit the coach immediately. “Don’t take chances” is the clear message you must impart to your drivers.

It’s crucial to understand that even though a small tire fire can sometimes be extinguished with the onboard extinguisher, the radial tire has super-heated pockets which could re-ignite the fire in a short time. Also, if an axle lacks proper lubrication or is slightly bent, it could heat up to a point where it starts the tire on fire, and you will not be able to cool it sufficiently enough to KEEP the fire out permanently. IT WILL START A FIRE AGAIN. Bottom line: Get all the passengers off the coach and to a safe distance away from harm. Make sure you check the restrooms, and then call for emergency assistance. Bus fires move quickly and can engulf the bus in just a few minutes. Concern for the safety of your passengers is the first order of business.

PART III – RESPONSE AND CONCLUSION

While we’re on the subject of driver response, the above action plan applies to all situations in which a driver or passenger detects smoke, heat or even senses that something is wrong. The driver should pull over to a safe area and, with fire extinguisher in hand, inspect the area of concern and the surrounding areas using a flashlight, “tire thumper” and other appropriate tools. The driver should inform the passengers of the situation and then take proper action. Even if the problem is solved, drivers must recognize the mere fact that because something out of the ordinary has occurred passengers will be concerned and anxious. Conventional wisdom suggests that it’s probably a good idea to stop at the next rest area where drivers can alert their management to what has occurred. Upon reboarding, reconfirm to passengers that the vehicle is safe to operate.

Severity Trumps Frequency

If you’re a typical operator, your safety efforts are directed at preventing the most frequent accident types, and you might not be thinking much about vehicle fires. The statistics reveal, however, that they are increasingly common. All it takes is one fire, large or small, and you’ll wish you had taken the time to deal with the items discussed. The average cost of a bus fire claim (for repair of the vehicle) is over $80,000. This does not include the potential for much higher costs if there are physical injuries to your passengers.

In addition to following good maintenance practice and staying on top of all recall notices, you should institute fire training for your drivers that includes passenger evacuation procedures. The time to learn about how to use a fire extinguisher or how to evacuate passengers is NOT during an emergency. Consider contacting your local fire department to provide basic training to your drivers. During pre-trip safety announcements, drivers must inform passengers how to evacuate the coach in case of emergency.
Finally, when purchasing new coaches be sure to ask about all safety features on board the vehicle, and get information on the fire suppression and fire pressure monitoring systems now available.

We can’t emphasize enough just how devastating the effect of bus fires can be to your company. If you add it up, it took 10 minutes to read this article, it will take 10 minutes to route it to your management staff and 10 minutes or so to review it with your drivers and mechanics. We hope this inexpensive 30 minute investment in fire safety will prevent potentially catastrophic consequences.
Historical Fires and their Impact on Regulations and Research

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ABSTRACT

Vehicle design is always changing rapidly as this market is very competitive and influenced by the latest technology. However, fire safety standards have not always been updated to reflect these changes in interior design, fuel used and vehicle use. Investigations and research have in many cases been conducted as a direct result of specific fires that have had a large impact on society due to high death tolls, financial loss or media attention. This paper presents several important fires and their implications for fire safety over the decades together with a short overview of some relevant research and some thoughts concerning the challenges we face ahead.

INTRODUCTION

Vehicles are part of everyday life today. As our transport systems needs to grow, vehicle density and use increases. The large number of people using different means of transport is a risk as fires or other incidents can result in catastrophic scenarios with high numbers of casualties. In particular, as transport systems become more complex, with terminals and hubs bringing different means of transport together such as trains, subways and buses, the risks associated with transport systems increases. In addition transportation in large cities is often underground adding considerably the risk for catastrophe in case of fire.

In addition to the potential to loss of life, fires and other incidents can result in large economic losses as exemplified by the fire in the Mont Blanc tunnel in 1999. The closure of the tunnel for three years meant that road vehicles had to take another route between Italy and France for that period of time directly resulting in large economic losses [1]. Clearly the repair of the tunnel itself was also associated with a significant cost not to mention the loss of lives [2]. Further, the impact on society from a vehicle fire in many cases is not only economic but could also have other safety related consequences such as loss of power, loss of data communication etc. which can have great implications for the modern society due to our inherent vulnerability where we are dependent on access to power and communication 24 hours a day [3].

Vehicles themselves have also changed considerably since their introduction but fire safety standards have not always been updated to reflect these changes. Initial development of the FMVSS 302 standard, e.g., was aimed at ensuring that highly flammable material was not allowed in largely open vehicles [4]. As the design of vehicles has changed and they have become largely enclosed with significant amounts of flammable material in the interior, this standard is no longer commiserate with the risk. Similarly, the type of fuel used, the speed of modern vehicles and the frequency of use have all changed significantly. Investigations and research have, in many cases, been introduced due to specific fires that have resulted in large impact on society in terms of death tolls, financial loss or high media attention. This paper gives a short insight into fires and their implications for fire safety over the decades together with a short overview of some of the work that is going on currently and some thoughts on challenges ahead.
HISTORICAL INCIDENTS AND THEIR IMPACT

The risk of a fire has been a key consideration in everyday use and development of vehicles since the first vehicles using different types of combustion engines were developed and used as an alternative to horses. The focus was initially on the protection of the vehicle from fires due to the burning of coal to produce steam in the steam trains and to prevent fires from the fuel in e.g. cars. As vehicles increased in popularity and became more common, the demand for comfort increased and other potential ignition sources, such as heating stoves in the carriages, were incorporated into the vehicles. The first vehicles were to a large extent constructed of steel and wood. Cushioning to make the seating more comfortable was limited and was typically made of e.g. leather, wool and other natural material.

The following contains a catalogue of incidents divided into different vehicle types, i.e. rail vehicles and road vehicles. The presentation is chronological rather than in order of importance and where possible an indication of the impact on regulations of the specific incident is given. The list is illustrative rather than exhaustive.

**Rail vehicles**

Fires in mass transport, such as trains, can cause significant numbers of deaths due to the high numbers of passengers and history shows some examples of tragic events that have in some cases resulted in development of fire safety requirements from the inception of this mode of transport. Numerous events have resulted in specific changes to regulations or standard practice as illustrated below.

The first steam trains became common in the early 1800’s. As early as 1842 an incident is recorded were a train derailed and caught fire on its way from the Kings fete celebration in Versailles to Paris resulting in 55 fatalities [5]. This fire led to the abandonment of the then-common practice of locking passenger in their carriages to protect them from falling out in France [6].

The derailment of the New York Express in Angola, New York in 1867 due to poor track condition and the subsequent fire due to stoves setting two coaches on fire resulted in approximately fifty persons being killed [7]. Known as the “Angola Horror”, the accident and the public's response influenced many railroad reforms including replacement of loosely secured stoves with safer forms of heating, replacing wooden cars with iron and requirements for better brakes [8].

A tragic derailment on December 29th in 1876, saw the Pacific Express fall into a frozen creek below the Ashtabula River bridge in Ohio due to structural collapse of the bridge [9]. A fire was started by the kerosene fueled stoves and a total of 92 people are killed due to the crash or fire. As a direct result of this incident cast iron was banned from use in constructing such bridges in 1888 [10].

In 1887 in January at least nine persons were killed due to the fire following due to a passenger train running into a stationary freight train in Ohio. The train was completely consumed in fire except the last two sleepers [11]. A month later 38 persons were killed in Hartford Vermont in a similar fire due to a fire caused by the kerosene lamps and coal heating.

The first major accident caused by an electrically powered train occurred in December 22, 1901 in Liverpool at the Dingle railway station when an engine caught fire and the train stopped about 80 yards before reaching the station. Soon all the train was on fire as well as the station and six people died. Investigation of this incident led both to the recommendation that trains and stations should contain as little wood as possible [12] and that electrical wiring should not be insulated with combustible material [13].

A fire in a Metro carriage in the Couronnes station in the Paris Metro in 1903 caused 84 fatalities [14]. The fire was caused by an electric short circuit in the motor. The accident led to several fire safety improvements including the adoption of multiple-unit train control (with a low-voltage control
circuit) and a second, independent power supply for station lighting, unobstructed exit routes in stations, lighted exit signs, insulation of electrical components, elimination of flammable material and installation of fire hydrants.

A number of severe train accidents occurred during the First World War. The death tolls were high in some of these due to severe overcrowding and the fires were in many cases caused by lack of locomotives causing train companies to resort to the use of old locomotives or overloaded locomotives. A list of the most significant incidents during WW1 are given below:

- May 22, 1915 a troop train collides with a stationary passenger train in the “Quintinshill rail disaster” in Scotland near Gretna hill. In addition, another passenger train crashed into the wreckage, which also involved two stationary freight trains. A fire then started, fed by gas from the lighting system, which consumed 15 of 21 cars in the troop train together with some cars of the other trains. The accident resulted in 226 fatalities.
- In December 1915, 18 persons were killed in a fire following the collision between a passenger train and a banking engine at St. Bedes Junction in England. The passenger train was gas-lit. A circular was sent out to all railway companies on the importance of replacing gas with electric lighting.
- The derailment and subsequent fire of a train carrying soldiers in Saint-Michel-de-Maurienne resulted in the death of about 700 persons in December 1917 [15]. The fire started in the night and lasted until the following evening, fed also by grenades and explosions. The fierceness of the fire and its long duration meant that only 425 of the victims could be identified.
- In January 1917 in Romania a derailment occurred due to lack of brake power on an overcrowded train with refugees and wounded soldiers [16]. The subsequent fire completely consumed the train and between 600 and 1000 passengers were killed.

In 1944 a runaway train hit the train in front of it in a tunnel nearby Torre del Bierzo in Spain resulting in a fire that killed between 78 and 500 people, the numbers are uncertain as strict censorship was applied during General Franco’s reign [17]. The initial incident was escalated when a third train ran into the crash due to lack of warning as signals had been destroyed by the first incident. The runaway train was unable to stop despite numerous attempts due to brake failure. As this incident occurred at a time when Spain was under strict control it is uncertain whether the incident resulted in any specific changes in regulations. It clearly illustrated the need for regular maintenance of train safety systems and a system in place to stop vehicles at the first sign of serious safety system failure.

In 1947 a passenger train collided with a stationary passenger train in Dugald Canada. After the collision a fire started and 29 persons were killed by the fires and only 2 from the collision [18]. The fire itself was so violent that only 7 of the bodies could be identified [19]. Once again this incident clearly indicates the dangers associated with wooden trains.

The Sakuragicho fire in Japan in 1951 was caused by a short circuit due to a cut overhead wire that was hanging down. The fire started on the roof of the carriage and the people inside were not able to open the electrically opened doors, resulting in 106 fatalities. The investigations after the fire resulted in requirements that the manual door openers placed under the passengers seats be better marked and the introduction of corridors between carriages [20].

A fire started from a short circuit caused by a collision between a passenger train and a freight train at Barnes railway station in London in 1955. The first coach of the passenger train was burnt out resulting in the death of 13 persons [21]. The investigation lead to numerous recommendations for improvements, including modernisation of the signalling system which at that time largely relied on signal operators manually changing the signal.

A tram caught fire in Oslo in 1958 resulted in five fatalities. The fire started in the front of the latter
car and was not immediately noticed by the driver in the first car who also operated the exit door. The fire resulted in recommendations that fire extinguishers, emergency exits and emergency door openers became mandatory in all collective transport.

In February 9, 1966, two coaches of a London-bound commuter train burst into flame as the train moved at 70 miles an hour, with scores of passengers jumping from the blazing cars before it was finally stopped near Radlett, 20 miles north of London [22]. Thirty-three persons, many of them stretcher cases with burns, were taken to hospitals but no fatalities were recorded. The year before 15 fires had occurred in this type of trains, miraculously without severe consequences. No reports have been found however on the causes to these fires and countermeasures taken.

The Taunton sleeping car fire in 1978 resulted in 12 deaths probably mainly due to carbon monoxide poisoning [23]. The fire was caused by plastic bags filled with linen placed against a heater in the vestibule. The rescue was hampered by locked doors. After the accident British Railway made clear that all doors had to be unlocked at all times and a decision was taken to use state-of-the-art fire prevention measures.

In 1995 a fire broke out in a Metro train in Baku [24]. The fire was probably caused by an electrical fault or sabotage. The train stopped in the tunnel 200 metres from the station, probably due to electrical fault. The tunnel was quickly filled with smoke. Escape was delayed by trouble in opening a door. At least 300 persons lost their lives. The Baku incident made it patently clear that it is imperative that evacuation start early and that space must be provided for passengers to evacuate beside the train.

The fire in Åsta in Norway in 2000 killing 19 persons was caused by two diesel trains collided [25]. The fire lasted for six hours. New departure routines for passenger trains were introduced as a direct result of this incident. After the incident only the engineer, and not both the engineer and conductor as before, were required to check that the main departure signal from a station showed "go" before the train started from a station.

The Al Ayatt train fire in Egypt in 2002 resulted in at least 383 deaths, the number is uncertain as the train was completely overloaded with people and many of the corps were completely consumed in the fire [26]. The fire started as a cooking gas cylinder exploded. Seven carriages were consumed to the ground. There was no communication between the rear end of the train and the driver so the train continued to drive for two hours after the fire had started. Recommendations on improved communication were a result of this incident.

The Daegu Subway fire in 2004 resulted in the loss of at least 198 lives [27]. The fire was started by an arsonist. The fire spread to the six carriages in the train. Many lives (79) were lost in a second train coming into the station were the initial train was burning. The passengers were trapped in the second train as it was prevented from driving away. The power was shut off to the trains due to the detection of the fire and the second train driver was advised to “run away and kill the engine” which locked the doors to the second at train. The fire resulted in that Metro carriages in South Korea were refurbished to improve fire standards.

In India, the Ladhowal train fire killed 39 people in 2003. Although the cause was uncertain it is suspected to have been started by a dropped cigarette or some electrical fault [28]. The fire spread extremely rapidly due to the open windows and the speed of the train, involving three carriages in a massive burst of flame within seconds. The initial fire development caused doors to be jammed shut hampering escape after the train had come to a halt.

In 2008 nine people died in a fire on board a Bulgarian State Railways train travelling from Sofia to the north-eastern town of Kardam in Dobrich region. The fire started in a carriage with 35 people as the train entered the town of Chervenbryag around midnight, and spread to a sleeping coach
containing a further 27 people. The fire took more than three hours to extinguish. Once again the
doors were locked which hampered evacuation [29].

A Eurotunnel Shuttle train carrying two vans and 25 lorries was severely damaged when a fire started
on one of the lorries in 2008 [30]. Six people were slightly injured, the part of the Channel Tunnel
where the train came to rest was closed for repairs for approximately six months. A total of 39
recommendations were made for improving the safety of the tunnel system including, e.g. suitable
education of personnel.

Fires on trains continue to occur at an alarming rate. In July this year, 32 people were killed in the
Nellore train fire in India [31]. The cause of the fire is still unknown but terrorist actions have been
hinted at. A commission has been proposed to investigate the incident but it is thought that antiquated
equipment and chronic overcrowding are the main causes of the fatalities.

**Road vehicles**

Information concerning historic bus, truck or car fires and possible impact on fire regulations is not as
prevalent as for train fires. This is probably due to the lower number of death in each accident (with
the possible exception of buses) and the fact that accidents are typically less spectacular with a
smaller vehicle if it does not include some dangerous goods. Clearly the number of road accidents
with ensuing fire is, however, significantly higher than the number of train incidents. Almost 4000
people are killed on the world’s roads each day [32]. Naturally not many of these deaths are related to
fires. Safety requirements on road vehicles are high but these are typically related to crash safety and
passenger safety in conjunction with a crash, not necessarily to fire safety per se. As indicated by
Digges et. al. [4], there is still much that can be done to improve fire safety in vehicles. Table 1
contains a selection of large road vehicle fires. The table is illustrative rather than exhaustive and the
incidents have been chosen as they have all resulted in multiple casualties, indicating the potential for
fatalities even in the case of road vehicles.

*Table 1. International road vehicle fires (without dangerous goods). Selection of incidents since 1980 [33].*

<table>
<thead>
<tr>
<th>Year</th>
<th>Accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Twenty three people were burned to death when a city bus caught fire in Minsk, Belarus after driving into a pool of gasoline spilled by a fuel truck.</td>
</tr>
<tr>
<td>1981</td>
<td>A bus carrying Hindu pilgrims swerved to the left of the road, and navigating a turn with brakes failed, caught fire at Srisailam, India, killing 61 people.</td>
</tr>
<tr>
<td>1982</td>
<td>Two buses carrying children collided with cars and burst into flames in Beaune, France, killing 53 people, including 44 children.</td>
</tr>
<tr>
<td>1983</td>
<td>A city bus crashed into a utility pole and caught fire on the outskirts of Bogotá, Colombia, in an incident caused by technical problems and excessive speed, killing 21 people.</td>
</tr>
<tr>
<td>1987</td>
<td>A bus veered into a high-voltage power pole and caught fire after colliding with another bus at Al-Kufayyah, Sudan, killing 64 people.</td>
</tr>
<tr>
<td>1988</td>
<td>A bus ignited after toppling into a ditch in Shaanxi, China, killing 43 people</td>
</tr>
<tr>
<td>1993</td>
<td>Three buses collided and ignited on a highway in Santo Tomé, Corrientes, Argentina, killing 55 people and injuring 70.</td>
</tr>
<tr>
<td>1994</td>
<td>A city bus caught fire and plunged 300-feet at national highway 1, Ca Pass, Vietnam, killing 28 people.</td>
</tr>
<tr>
<td>1997</td>
<td>Forty eight people, most of whom were university students, were killed in a collision of an empty gasoline tanker truck and a passenger bus in Karapınar on Konya-Ereğli motorway. The passengers were trapped in the bus when both vehicles got afame. The accident led to wide debate on fire-safety standards of passenger buses.</td>
</tr>
<tr>
<td>1999</td>
<td>The Fire in the Mont Blanc tunnel between France and Italy March 24th. The tunnel had to be closed for three years after the fire. The fire resulted in several fire safety measures in the tunnel and has also had a large impact on tunnel research and fire development</td>
</tr>
<tr>
<td>Year</td>
<td>Event Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------------</td>
</tr>
<tr>
<td>1999</td>
<td>The fire in the Tauern Tunnel in Austria started as a truck collided with a waiting queue when one lane was closed due to construction works. The fire resulted in severe damage on the tunnel and the death of five persons. The incident led to improvements in the Austrian tunnel guidelines concerning pavement, escape means, ceilings support etc.</td>
</tr>
<tr>
<td>2002</td>
<td>An Ayacucho–Lima regular route bus burst into flames, before skidding out of control and hitting a gasoline station at Chincha Alta, Ica, Peru, killing 35.</td>
</tr>
<tr>
<td>2003</td>
<td>December 20 – A German tourist bus smashed into a concrete highway barrier and burst into flames in Hensies, a town on the Belgian border with France, killing 11 people and injuring 37 others</td>
</tr>
<tr>
<td>2005</td>
<td>24 elderly people died when their bus caught fire as they fled Hurricane Rita near Wilmer, Texas</td>
</tr>
<tr>
<td>2006</td>
<td>A bus catches fire in downtown Panama City, killing 18 people</td>
</tr>
<tr>
<td>2007</td>
<td>A bus travelling from Dhaka to Chittagong crashes and catches fire near Comilla, Bangladesh, killing from 55 to 70 people</td>
</tr>
<tr>
<td>2008</td>
<td>According to GEO Television of Pakistan report, a Lahore-Multan passenger bus carrying over 60 people caught fire after going off a bridge outside Pattoki, Bunjab of Pakistan, killing 40 and injuring 22</td>
</tr>
<tr>
<td>2008</td>
<td>A bus travelling from Chittagong hit a pole carrying a power line and caught fire at Cox's Bazar, Bangladesh, killing at least 16 and injuring 20.</td>
</tr>
<tr>
<td>2008</td>
<td>A bus carrying 22 university students collided with truck in Iran. Both vehicles caught fire immediately after the crash killing 22 and injuring 7.</td>
</tr>
<tr>
<td>2008</td>
<td>A bus overturned and caught fire, when trying to overtake a trailer on the outskirts of Kingo, Uganda, killing 40.</td>
</tr>
<tr>
<td>2008</td>
<td>A bus bound for Maputo carrying mine workers of Mozambique, left the road, and burst into flames with collided a tree at outskirts of Komatipoort, Mpumalanga, South Africa, killing 17</td>
</tr>
<tr>
<td>2009</td>
<td>The Chengdue bus fire was probably caused by gasoline carried onboard which was ignited by mistake or deliberately. The fire killed 29 people</td>
</tr>
<tr>
<td>2010</td>
<td>Eighteen people killed when a passenger bus collided with a truck, burst into flames, and flipped over in central Mexico</td>
</tr>
</tbody>
</table>

Clearly fire spread in interior materials once the fire has entered the passenger compartment is very rapid allowing little time for safe egress. In passenger cars this may be of marginal importance if the passengers are free to evacuate at the onset of the fire but if they are trapped, e.g. as the result of a crash, rapid evacuation may be impossible. Further, in mass transport vehicles with the greatest potential for multiple fatalities, rapid spread of fire in the interior material is certainly an important factor hindering egress.

**RESEARCH AND REGULATION CHANGES TODAY**

Considering the development seen in many vehicles today and over the decades with an increased use of plastics it seems that we have forgotten the lessons learned over the years such as minimizing the amount of combustible material. The amount of plastics in vehicles today is huge but safety standards developed in the 1950 and 1960s are still relied on to protect vehicles. Today cigarettes are much less common in vehicles, instead the ignition sources are electrical systems, friction heat and fires starting in the engine compartment due to lack of maintenance such as cleaning and checking of fuel leakages.

Growing awareness of the increasing frequency of bus fires which had increased in the early 2000 century [34] in Scandinavia initiated research funded by the Swedish and Norwegian Road Authorities [35]. Due to the large potential risk for catastrophic fires resulting in many casualties, the Norwegian and Swedish road administrations initiated a bus research project in 2005, “Bus Fire Safety,” in conjunction with SP Technical Research Institute of Sweden. The overall objective of the
project was to investigate the fire safety of buses and to produce recommendations for improvements. Following completion of the Bus Fire Safety research project, the SP Technical Research Institute of Sweden has been engaged in international bus fire safety education. Swedish technical experts presented proposals for better test procedures for materials at the UN United Nations Economic Commission for Europe (ECE) Working Group on General Safety Provisions (GRSG).

Important work is ongoing to change the regulations and some breakthroughs have been reached lately with the change of UNECE Regulation 107 to require fire detectors in engine compartments in buses from 2012/2013. Regulation 118 is updated to require testing of cables and insulation material in engine compartments must be resistant to the absorption of oil or fuel. Discussion have also recently finished on further updates of R107 and R118 with requirements for detectors in confined spaces in R 107 and, for R118, requirements on burning velocity and that materials to be mounted vertically also are tested vertically. Discussions are also going on to introduce suppression systems in the engine compartment and emergency exits in Regulation 107.

Examination of US data [36] indicates that overall vehicle fires are decreasing significantly for the time period 1990-2009 period. Despite the encouraging fact that the number of vehicle fires is decreasing this is still a significant problem. Significant research has been prompted by the scale of the problem, e.g., in response to the Wilmer bus fire in the US in 2005, the Volpe National Transportation Systems Center performed a study for the Federal Motor Carrier Safety Administration (FMCSA), the objective of which was to gather and analyze information regarding the causes, frequency and severity of motorcoach fires caused by mechanical or electrical failure. As a result of this study, the US Department of Transportation issued a Motorcoach Safety Action plan [37]. In this plan, the National Highway Traffic Safety Administration (NHTSA) identified the need to upgrade motorcoach fire safety requirements and to evaluate the need for a Federal Motor Vehicle Safety Standard that would require installation of fire detection and suppression systems on motorcoaches.

In 2008, NHTSA initiated a two-year fire safety research program with the National Institute of Standards and Technology (NIST) [38]. The objective is to better understand wheel well fires and their propagation into the passenger compartment, the vulnerability of the passenger compartment to such fires and countermeasures and detection systems.

Although there is no national requirement or standard for Automatic Fire Suppression Systems (AFSS) on buses, there are individual requirements at the state level. In addition, some Original Equipment Manufacturers (OEMs) and operators have voluntarily chosen to install automatic fire suppression systems. The commercial coach market began making automatic fire suppression systems standard on buses equipped with wheelchair lifts, and optional on some buses more than five years ago. City transit buses have been using AFSS for more than 15 years. Early adoption was driven by concerns over risks associated with alternate fuels such as methanol. Today, the majority of transit operators in the US are specifying AFSS on their buses.

However, US federal regulations only require that a bus carry a small fire extinguisher, even though there is little possibility that a fire extinguisher will be useful in extinguishing a typical bus fire. At Lancer Insurance Company, the largest insurers of buses in the US, nearly two dozen bus fires are reported each year. The majority of these fires are electrical, turbo or brake related, and they generally engulf the engine compartment. Without a fire suppression system, these fires often result in serious physical damage to the bus [39].

Clearly, fire suppression systems are more effective in managing bus fires. They also give passengers precious time to evacuate. Bus fires are a serious issue in the US and will continue to be a potentially fatal hazard until there are efficient tools to fight the fire, requirements for better engine maintenance and adoption of widely recommended safety measures.

Similarly, Swedish insurance industry statistics indicate that the number of total losses due to bus fires can be reduced dramatically by the introduction of requirements for fire suppression systems in
engine compartments. Prior to 2004, there were six to seven complete burnouts of buses annually in Sweden due to fires that started in the engine compartment. In 2004, Swedish insurance companies took the concerted action to require that all (insured) buses be equipped with a fire suppression system in the engine compartment. Since then, no insured bus has been completely consumed by such fires.

Requiring a suppression system is, however, not sufficient to ensure safety. It is important that the system has proven performance. Test methods for extinguishing systems are currently developed in Sweden. This work has also identified the need for detections systems in the engine compartment together with test methods for these. Further research is necessary to define performance requirements for detection systems.

Even if these are important steps forward, the fire requirements for road vehicles carrying passenger are far behind the requirements for rail transport. Traditionally the fire safety requirements in trains have been national and in many cases based on building codes. In Europe the development of a fire safety standard for trains started in 1991. This work resulted in that the Technical specification TS 45545 was published in 2009 [40]. The TS is now out on ballot to become a standard, EN 45545. EN 45545 has adopted a Fire Safety engineering perspective and contains requirements adapted to the fire scenario on Ignitability, Flame spread, Heat release rate, Combustibility, Smoke production, Toxic gas production and Fire resistance. The standard is based on work carried out in e.g. FIRESTARR [41] and lately Transfeu [42].

The Federal Railroad Administration in USA issued their passenger rail equipment regulations 49 CFR Part 238 in 1999, these were based on safety Guidelines for materials in rail cars developed in the 1980s. The FRA regulations are prescriptive but the test methods referred to are similar to those in EN 45545. There are, however, no requirements on toxicity of the fire effluents that is a major discussion in Europe including the measuring methods to be used for this. In fact the ongoing European project Transfeu focuses to a large extent on the toxicity and suitable test methods.

Research today is also focused on the fire safety challenges introduced by the use of alternative fuels and drives. Several presentations in FIVE 2010 focused on the risks associated with hydrogen powered vehicles, lithium ion batteries and new fuels in general [43]. The Fire Protection Research Foundation has an ongoing research program on fires risks with Lithium-ion batteries [44]. Alternative drives will be an area of high importance for the coming years as new energy carriers are developed and we will see a mixture of different fuels on the roads for the years to come.

**CHALLENGES FOR TOMORROW**

Who knows what the future will bring, will we be using road vehicles as we know them at all or will we use completely new means of transport. Most future scenarios include an increase in population over the world and the major increase in the emerging economies such as Africa and Asia (exclusive Japan). In addition, the population will continue to age, move to cities and become wealthier [45]. This will put higher a demand on the transportation system, which needs to transport more people in a more comfortable and safe manner on a smaller space. This, in turn, will place high demands on the fire safety in particular as increased congestion can result in large death tolls.

Perhaps will we see significant changes in how people use different transport means, in particularly in light of the growing individualism and globalization. There have already been attempts to design cars that drive themselves and there are examples of subways without drivers. The only obstacle is probably that people do not yet feel comfortable without a driver, but this will certainly change over generations.

Another change that is apparent today is the growing demand for different entertainment media during transport. These systems might not only distract the driver but also introduce new fires risks as new devices are introduced into the vehicles electrical and communication system increasing the risk for
malfunction and fires.

One clear trend in the near future is a continued movement to minimize emissions from the transport sector. This will probably result in an increased use of lightweight material in the vehicles since a light construction means good fuel economy and less emissions. However, lightweight materials may be easy to ignite and produce high heat release when burning which will put a higher demand on fire protection. More research is necessary to solve issues associated with fire performance of such materials. The Fire-Resist project presently underway in Europe is looking at this specific issue related to rail, air and sea vessels [46].

The increased emission requirements on ICE engines will further result in higher engine temperatures in some cases. This is a potential for an increase in engine compartment fires and therefore calls for research efforts.

In addition will we see more and more alternatively propelled vehicles instead of ICE vehicles. Research is already ongoing here in order to make these vehicles as safe as possible in particular as fires and accidents in the early use of any kind of new vehicle can hamper the introduction into the market, e.g. the European project Smartbatt considers the smart and safe integration of battery systems into fully electric vehicles.

Fire safety is and will continue to be an issue for all future means of transport. Means to meet the safety standards will differ and a solution that works for one type of vehicle might prove to be inefficient for another type or fuel. The rapid and diverse development of different vehicles will call for careful design and new methods in order to make sure that the fire safety is not compromised in order to meet other requirement. This will require a holistic view of the entire infrastructure including fuel distribution.

CONCLUSIONS

The present overview of historical incidents shows that while we have learnt from fire accidents, much still remains to be done. Important initiatives for rail safety are approaching completions but fire safety in road vehicles continues to lag behind that of other modes of transport.

Important research has supported international and national regulations historically and ongoing initiatives continue to provide necessary input for the future.

We do not know how future vehicles will look or how they will be propelled but clearly safety including fire safety will continue to be key to their acceptance into future markets.

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Fire Protection Strategies for Lithium Ion Batteries: 
_a status update from the Fire Protection Research Foundation_

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Fire Protection Research Foundation.
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ABSTRACT
In 2010, the Fire Protection Research Foundation began a research program to develop the technical information to inform protection criteria for storage of lithium ion batteries. The program consists of a hazard assessment and a flammability characterization study. In 2012, in response to a need to inform national training programs for emergency response to electric vehicle incidents involving lithium ion batteries, the Foundation initiated a related research program to develop best practices for firefighting tactics, PPE, and overhaul for these incidents. The paper summarizes the current status of these programs.

KEYWORDS: Lithium ion batteries; fire protection, fire fighting

INTRODUCTION
Lithium ion battery cells and small battery packs (8 to 10 cells) are in wide consumer use today. Superior capacity has driven the demand for these batteries in electronic devices such as laptops, power tools, cameras, and cell phones. Vehicle manufacturers are bringing electric and hybrid electric vehicles to market using large lithium ion battery packs (several thousand cells). Lithium ion batteries can experience internal short circuits due to internal defects (production issues), physical abuse (handling issues), or exposure to high temperature (fire). Once an internal short develops, a sudden release of stored energy occurs. This event can cascade thru adjacent cells within a battery pack or a pallet load. Unlike most commodities, fires involving lithium ion batteries can initiate within the product. In storage, this means a fire can initiate within a pallet load and beyond the influence of conventional fire protection systems. As a note, one pallet may hold 60,000 lithium ion cells. It is recognized that lithium ion battery manufacturers are pursuing a variety of chemistries, geometries, and safety features to reduce or manage the hazards associated with lithium ion batteries.

As these batteries are widespread in commerce, they are also increasingly widespread in storage and transport. Fire protection systems and strategies must be developed to address safety of facilities and personnel in this portion of the battery life cycle.

The National Fire Protection Association (NFPA) develops a number of international standards for fire protection for hazardous commodities. NFPA 13, Standard for the Installation of Automatic Sprinklers (2), provides specific guidance on protection of stored commodities with known hazard classification.

In 2010, the Fire Protection Research Foundation, NFPA’s research affiliate, began a research program to develop the technical information to inform protection criteria for NFPA 13. This program has two phases: a hazard assessment and a flammability characterization study.
Concurrently, NFPA initiated a training program for emergency responders to guide response tactics for electric vehicle emergency incidents. This program is based on NFPA standards related to emergency response, including:

- NFPA 1410, Standard on Training for Initial Emergency Scene Operations
- NFPA 1500, Standard on Fire Department Occupational Safety and Health Program
- NFPA 1620, Standard for Pre-Incident Planning
- NFPA 1971, and others, Personal Protective Clothing and Equipment Standards
- NFPA 1936, and others, Extrication Equipment Standards

In 2012, the Foundation initiated a research program to inform those tactics that relate to incidents involving lithium ion automotive batteries.

This paper will review the research plans and preliminary results from both these programs.

**LITHIUM ION BATTERY HAZARD ASSESSMENT AND GAP ANALYSIS**

In 2010, the Foundation commissioned 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. The report (1) is a valuable resource on hazards associated with storage and use of these batteries.

Based on this information, a gap analysis and research approach toward evaluating appropriate facility fire protection strategies was developed.

*Table 1: Gap Analysis*

<table>
<thead>
<tr>
<th>1. Leaked electrolyte and vent gas composition</th>
<th>2. Commodity specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Detection of cell leakage or vent gases to alert response</td>
<td>2.1 Establishment of commodity classifications for lithium ion batteries including:</td>
</tr>
<tr>
<td>1.2 Alarm and evacuation thresholds for cell vent gases</td>
<td>2.1.a Bulk packaged cells</td>
</tr>
<tr>
<td>1.3 Evaluation of cell vent gas flammable range</td>
<td>2.1.b Large format battery packs</td>
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<td>2.1.c Consumer goods containing lithium ion cells or packs</td>
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<tr>
<th>3. Suppressants</th>
<th>4. Incident cleanup</th>
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<tr>
<td>3.1 Development of automatic sprinklers protection guidelines for bulk packaged cells</td>
<td>4.1 Methods of fire overhaul (fire service final extinguishment actions)</td>
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<tr>
<td>3.2 Development of automatic sprinklers protection guidelines large format packs</td>
<td>4.2 Handling, examining and disposal of damaged lithium ion cells and packs.</td>
</tr>
<tr>
<td>3.3 Development of automatic sprinklers protection guidelines consumer goods containing lithium ion cells or packs</td>
<td></td>
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<tr>
<td>3.4 Understanding the environmental impact of fire protection water runoff</td>
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<tr>
<td>3.5 Exploration of other fire extinguishing agents such as foam and water mist</td>
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<tr>
<td>3.6 Exploration of fire extinguishing agents vs. fire stage</td>
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</tbody>
</table>
PHASE II RESEARCH

The focus of the Foundation’s Phase II research program is on gaps 2 and 3 above - commodity specification and protection criteria.

Battery Description

Based on the previous hazard assessment, and a related storage survey, the scope of this program will include three different battery types:

- 18650 format cylindrical lithium ion batteries
- Prismatic lithium ion batteries in polymer gel packs
- Packaged power tool rechargeable battery packs with cylindrical cells

These product types represent the most commonly found small format cells in commerce; the power tool packs represent a common packaging configuration in storage environments.

Background on Commodity Specification

Commodity classifications for water-based suppression strategies are described in NFPA 13 and relate directly to the fire protection system design requirements.

Classification of actual commodities is primarily based on comparing the commodity to be protected to the definitions for the various commodity classes. NFPA 13 provides a list of commodity classes for various commodities. Once the commodity classification is known along with the geometry and configuration of the stored product, sprinkler design densities can be selected. Different types of batteries and the recommended commodity classification for those batteries are mentioned:

- Dry cells (non-lithium or similar exotic metals) packaged in cartons: Class I (i.e., alkaline cells);
- Dry cells (non-lithium or similar exotic metals) blister packed in cartons: Class II (i.e., alkaline cells);
- Automobile batteries – filled: Class I (i.e., lead acid batteries with water-based electrolyte); and
- Truck or larger batteries, empty or filled Group A Plastics (i.e., lead acid batteries with water-based electrolyte).

Currently, NFPA 13 does not provide a specific recommendation of a commodity classification for Li-ion cells or complete batteries containing several cells. A number of features specific to Li-ion batteries could make any of the existing battery classifications inaccurate and the recommended fire suppression strategy may not be appropriate:

- Flammable versus aqueous electrolyte;
- The potential to eject electrodes / case material (projectiles) upon thermal runaway;
- Latency of thermal runaway reactions (cell venting can occur sequentially and after a significant delay resulting in re-ignition of materials);
- Large format battery packs may exhibit voltages much higher than typical truck batteries; and
- Individual cells generally have metal versus plastic outer shells.
The venting and projectile potential of Li-ion cells has some similarities with aerosol products, which typically utilize a flammable propellant, such as propane, butane, dimethyl ether, and methyl ethyl ether. However, these products generally have no associated electrical energy and are not as susceptible to re-ignition events. As they contain flammable electrolyte, Li-ion cells might also be compared to commodities such as ammunition or butane lighters in blister packed cartons (high-energy density).

For commodities not specifically covered by NFPA 13, full-scale fire suppression tests are typically used to determine the commodity classification. Most current sprinkler system design criteria are based on classifications of occupancies or commodities that have been developed from the results of full-scale fire suppression test data and the application of experimental results that have been shown to provide a minimum level of protection.

One of the main reasons that specific test data are required when determining the commodity classification of a new or unknown commodity is that the current ability of an engineering analysis is insufficient to define sprinkler suppression characteristics (3). At present, there is no publicly available large-scale fire test data for Li-ion cells that can be used to fully assess the storage hazards of Li-ion cells or batteries or to determine an appropriate commodity classification that could be used to provide an overall fire protection suppression strategy.

Flammability Characterization

The standard approach to classify bulk packaged materials described above is not feasible for Li-ion batteries due to excessive cost and difficulties acquiring the necessary quantity of product. Therefore, a test was desired that captures the flammability characteristics inherent in a rack storage fire while limiting the total quantity of test commodity to one pallet load. This methodology cannot provide the same information as the Commodity Classification protocol or a Large-scale fire test and is only applied due to the excessive cost, difficulty acquiring, and disposal issues of Li-ion batteries.

The methodology developed for this project by FM Global (who is conducting this portion of the project) consists of a comparison of the free-burn flammability characteristics of Li-ion batteries and standard commodities in a rack storage array. Testing will be conducted under the 5 MW Fire Products Collector located at the FM Global Research Campus in West Glocester, RI.

Combustion gases will also be analyzed to measure the convective and chemical (oxygen depletion and carbon monoxide/dioxide generation) heat release rates. Recognizing that the chemical heat release rates for testing with Li-ion batteries will have an unknown measurement error introduced by additional sources of carbon dioxide in the vent gases.

Tests are scheduled for September of 2012; the final report will be made available on the Foundation’s website by year end.

Best Practices for Emergency Response to Incidents involving EV Battery Hazards

Background

In 2009, NFPA began a partnership with U.S. Department of Energy (DOE) and the automotive industry to develop and implement a comprehensive training program for emergency response to electric vehicle (EV) incidents. Currently, this program provides safety training to emergency responders (25,000 to date) in order to prepare them for their role in safely handling incidents involving EVs. It has a lack of data to draw on to address the potential hazards associated with damaged EV batteries.
The National Highway Traffic Safety Administration (NHTSA) has recently approached the NFPA to review the OEM (original equipment manufacturer) information on emergency response tactics for EV incidents involving battery hazards and assist in developing guidance for emergency responders. A preliminary review indicates that there is inconsistency and lack of technical substantiation for procedures associated with these incidents. In particular, NFPA has observed that although many manufacturers have provided procedures related to vehicle extrication processes (associated with collisions), there is very limited publicly available validated information regarding response to fires involving electric vehicles, and towing and dismantling/disposal associated with damaged battery incidents.

Emergency response personnel are accustomed to responding to conventional vehicle fires, and generally receive training on the hazards associated with vehicle subsystems such as airbag initiators and seat belt pre-tensioners. Electric vehicles pose new unknowns; emergency responders have questions regarding:

- Appropriate personal protective equipment (PPE) to be used for responding to fires involving EV batteries:
  - Is current PPE appropriate with regard to respiratory and dermal exposure to vent gases and combustion products?
  - Is current PPE appropriate with regard to potential electric shock hazards?
  - What is the size of the hazard zone where full PPE, including respiratory protection, must be worn?
- Tactics for suppression of fires involving EV batteries:
  - How effective is water as a suppressant for large battery fires?
  - Are there projectile hazards?
  - How long must suppression efforts be conducted to place the fire under control and then extinguished? What level of resources will be needed to support these fire suppression efforts? Is there a need for extended suppression efforts?
  - What are the indicators for instances where the fire service should allow a large battery pack to burn rather than attempt suppression?
- Tactics and PPE to be used during overhaul and post-fire clean-up operations
  - How long should fire scenes be monitored for re-ignition events? What tools and metrics are available?
  - What hazards should fire-fighters be aware of during overhaul (e.g. partially energized battery packs or delayed thermal runaway reactions)?
  - What can be done to effectively identify and neutralize hazards encountered during overhaul?
  - What are appropriate damaged battery condition assessment, handling, towing and dismantling/disposal procedures?

Scope

The scope of this project is to develop the technical basis for best practices for emergency response procedures for EV battery incidents to include:

1. Firefighting – PPE, suppression methods and agents, and clean-up/overhaul operations
2. Post incident procedures - Damaged battery condition assessment, handling/isolation and tow/removal; de-energizing/discharging (as appropriate) and disposal (This activity will be limited to the compilation of existing case studies, best practices and possible field techniques.)
Activities

1. Firefighting Tactics – PPE, suppression tactics, and clean-up/overhaul operations for EVs
   - Review industry best practices for firefighting (e.g. PPE, suppression tactics and agents, clean-up) as available
   - Identify, characterize and prioritize battery technologies and representative battery types. For the purposes of testing in this program, a lithium ion battery technology with capacity of 5.0 DC kWh or larger if designed for a PHEV or EREV, and 15.0 DC kWh or larger if designed for a BEV will be selected.
   - Identify key required elements of emergency response PPE, tactics, and overhaul operations
   - Develop and implement full scale fire testing plans for each battery pack to be tested. This will include:
     - Working with the battery pack manufacturers to identify an appropriate “package” for full scale testing. For example, a package may include a battery pack, its associated cooling system, and its mounting location (e.g. vehicle floor pan, trunk assembly, etc.)
     - Identifying, procuring, and modifying an appropriate vehicle fire trainer that can be modified to accommodate the various testing packages, provide an appropriate ignition source for the testing packages, and provide sufficient screening of individual battery packs during fire tests to maintain confidentiality of project participants
     - Identifying appropriate methods and equipment for measuring basic fire hazard parameters during fire testing in this scenario, including temperature, duration, heat release rate, products of combustion, etc as well as suppressant application approaches, and potential hazards associated with overhaul and cleanup
     - Developing a plan (with OEM input) for charging battery packs prior to testing and safe discharge/removal after testing
     - Conduct full scale fire testing to include one unsuppressed combustion test, followed by 2-4 tests with selected suppressants/tactical approaches
   - Report on:
     - Comparison of results between unsuppressed and suppressed scenarios, different battery types (if possible), and traditional vehicle full scale fire tests
     - Suggested emergency responses approaches for fire fighting to include PPE requirements, extinguishing agents and quantities/duration and fire scene overhaul

2. Post Incident Procedures Best Practices: Damaged battery condition assessment, handling/isolation and tow/removal; de-energizing/discharging (as appropriate) and disposal/recycling
   - Review and compile case studies and industry best practices for handling, isolation, storage, de-energizing and discharging (as available)
   - Identify possible field techniques for battery damage assessment and monitoring (for example thermal imaging cameras, gas monitoring), de-energizing and discharging (as appropriate)

The findings from this project, completion anticipated fall of 2013, will be integrated into NFPA’s ongoing national EV training programs.
CONCLUSIONS

As lithium ion batteries continue to enter the stream of commerce in large and small formats, the research programs described above will inform safety codes and standards for storage and emergency response.

REFERENCES


Fire Suppression Systems in Buses and Coaches – How, Where and Why

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ABSTRACT

In most forms of public transportation, and on trains, ships and aircraft, there are rules and regulations requiring some form of fire protection in areas identified as fire risks. In all of the forms of transportation listed, the engine compartment requires both fire detection and fire suppression. Although there are some regulations requiring both on buses, it is very limited. In recent years, there has been a growing interest by many countries to address this issue.

This paper will examine how fires occur on buses, where systems are being installed, and what regulations are in place or being considered. The question of “why” can be broken into two parts: 1. Why should you consider an Automatic Fire Suppression System? 2. Why do people choose to use fire protection?

The majority of the information in this paper is focused on the United States (U.S.) because the author has the most experience and background in that region. Information provided regarding other countries is based on internet information, market intelligence, and limited meetings/visits to legislators, bus manufacturers and operators.

KEYWORDS: Automatic Fire Suppression System, Fire Detection, Fire Suppression

INTRODUCTION

Prior to the internet, cell phones with cameras and video capabilities, information regarding bus fires would have been very localized. Today, we have a broader awareness of bus fires, and performing an internet search on bus fires would result in pages and pages of bus fire information. What we don’t see are any reports of automatic fire suppression systems actually extinguishing fires, but the manufacturers of these systems receive numerous reports of systems successfully detecting and suppressing bus fires.

Having said that, just installing an Automatic Fire Suppression System does not mean that if you have a fire, it will detect and extinguish the fire, allowing you to restart the bus and drive away. The design and application of a suppression system is very critical to its performance and should only be done by a specially trained person with experience in Special Hazards Fire Protection. It takes years of knowledge to properly assess the fire risk, determine the best fire detection and suppression methods, and then decide what is the proper location of the detection and suppression devices. Hopefully, this paper will give you a brief overview of the types of fires that occur on buses, how they occur, and the scope of what analysis has to be made when selecting an Automatic Fire Suppression System. The reference list not only includes information contained in this article, but also includes references that can be used to gain further knowledge about bus fires, fire detection and fire suppression systems.
HOW FIRES START ON BUSES

How fires occur on buses is really no different than other similar hazards (i.e., boats, trains, etc.) that contain a flammable fuel powered engine with the associated starting, charging and other equipment. (One unique aspect regarding buses, compared to the other hazards noted, is that buses also have rubber tires and wheel wells which pose an additional fire hazard.) A fire can occur due to failure or malfunction of a component resulting from maintenance, design, or even a collision or arson. However, for the fires to occur three components of the fire triangle: heat, fuel and air (oxygen) must exist.

Reports [1], [3], [4], [6] show that the majority of bus fires occur in either the engine compartment or the wheel well compartment. The table below highlights how the operational characteristics of a bus can change the occurrence and type of fires that occur. For instance, coaches travel much longer distances than transit (city bus), and the occurrence of wheel well fires is much higher as a result of the wheels turning for long periods of time.
TYPES OF BUS FIRES

1) Flammable Fuel Fires
Flammable fuel fires are caused by a leak or rupture from a fuel source, which then comes in contact with a heat source (such as a turbo charger) that has heated to a temperature above the liquids/gas ignition level. The most likely ignition point is the turbocharger and exhaust components.

2) Electrical Fires
Electrical fires are caused when there is chaffing/abrasion of the insulating material which then exposes the conductor. Once grounded, a short or arcing condition is created, which causes the cable to overheat. This in itself may or may not produce visible flames, especially in the early stages. As the temperature and time increases, other flammable materials may become involved, and the risk of a fire spreading to other areas increases.
3) Friction Fires
Friction-based fires typically are associated with wheel bearing failure, dragging brakes, underinflated tires or even a locked A/C compressor clutch. These fires are similar to electrical fires in that they do not typically produce flames in the early stages. In fact, they may be much slower than electrical fires, depending upon how much heat is being generated and the mass of the material. Unfortunately, some of these events, specifically those involving tires, can be difficult to detect and even more difficult to suppress.

WHERE ARE FIRE SUPPRESSION SYSTEMS USED

If you operate buses anywhere in the world, it is safe to say that you have had or will have a fire. The frequency and severity of the fire are based on the earlier discussions on how and what types of fires occur. Some of the fires, especially those with loss of life, are well publicized. Unfortunately, most go unreported.

In some cases, the Original Equipment Manufacturers (OEM), or operators, have voluntarily decided to install fire protection. In other cases, the government or authority in charge is considering or has implemented rules or regulations that require installation of fire protection. The simple fact that we are now attending the second Fires in Vehicles Exposition demonstrates that the concern about bus fires and how to prevent them is growing.

In 2010, a group of European bus manufactures voluntarily signed an agreement to fit all new coaches and buses for delivery to European Union (EU) member states with fire detection systems in the engine compartment and around the auxiliary heater.

Although the usage of fire suppression systems on buses is small and legislation is limited, the concern and interest is growing. A brief overview of some of the major incidents that have happened around the world, and information relating to legislation or other forms of requirements, is detailed below.

Australia

Australian Standard – Fire protection for mobile and transportable equipment. The standard originated as Australian Coal Association Research Program, Draft Code of Practice Fire Suppression Systems for Off-Road Mobile and Transportable Vehicles, but was expanded for applicability to vehicles and transportable equipment in other industry sectors which includes buses.

The standard is very thorough with sections on Fire Risk Management/Reduction and Safety Requirements, as well as sections relevant to the design, installation, commissioning and maintenance of the fire protection systems. All systems are required to be listed with recognized testing and approval boards, and pre-engineered systems are required to undergo endurance and function testing.
Hong Kong

A fire at the Tin Shui Wai Depot during the night of March 31, 2008, caused severe damage to 10 buses.

A press release [13] in January of 2009 stated that “on December 10 of last year three buses caught fire or emitted smoke while in motion and such a situation has given rise to public concern.” The release also states that the Transportation Department (TD) “attaches great importance to the fire-fighting system on franchised buses. The department is now working with the bus companies on a number of options, such as automatic fire extinguishing system, automatic shutdown of air-conditioning ventilation system in case of fire and enhancement of the fire protection zone, in order to further safeguard the safety of passengers.”

Subsequently several fire protection system manufacturers were given a chance to test their products in a test cell that was the size of a typical engine compartment, utilizing a freestanding fan to simulate airflow and diesel soaked newspapers as a fire source.

Finland

Following an official investigation by the Accident Investigation Board of Finland, a Bus Fire Project was started which resulted in two Incident Reports [1] and the following proposed rules:

- New buses will be equipped with automatic or semi-automatic fixed fire extinguisher systems, including at least one fire alarm sensor close to the engine cylinder head.
- All buses should be equipped with a 6kg hand extinguisher or two 2kg hand extinguishers.
- Engine compartments will be built with holes for fire extinguisher nozzles.
- Improvements will be made in fire resistance of engine compartment soundproofing.

Israel

A steering committee on bus fires has decided to approve the creation of a new Israeli Standard for Automatic Fire Suppression in Buses, subject to finding a funding source. Several bus OEMs have already installed both fire detection and fire suppression systems.

Germany

On November 4, 2008, a tour bus returning from a day trip to a farm, caught fire on a highway near the northern German city of Hannover, killing 20 people.

In the fall of 2011, BAM, the Federal Institute for Materials Research and Testing, invited fire protection system manufacturers to install fire suppression systems on an operating bus to test their effectiveness on live fires based on the SP Technical Institute of Sweden (SP) test protocol. Additional fire suppression tests, along with tests of fire detection devices, will be conducted in August of 2012.

Turkey

There currently is no regulation. But, a recommendation has been made to the bus industry to install fire detection systems in the bus engine compartment of new vehicles. Several bus OEMs have already installed both fire detection and fire suppression systems.

At the recent BUSWORLD Expo held in Istanbul, a special meeting and presentation regarding bus fires was held.
Sweden

Swedish insurance industry statistics indicate that the number of total losses due to bus fires can be reduced dramatically by the introduction of requirements for fire suppression systems in engine compartments. Prior to 2004, there were six to seven complete burnouts of buses annually in Sweden due to fires that started in the engine compartment.

In 2004, Swedish insurance companies took the concerted action to require that all (insured) buses be equipped with a fire suppression system in the engine compartment. Since then, no insured bus has been completely consumed by such fires. Still, at least 40 percent of buses in Sweden are not equipped with fire suppression systems because they either aren’t insured or are self-insured.

SP is leading the way in providing a realistic test platform and test protocol that can test the effectiveness of fire suppression systems. Preliminary tests have been ongoing and certification testing is scheduled to begin later this year.

United States

The U.S. has federal, state, city, county and local regulations and jurisdictions. With 50 states and as many as 30,000 cities, the regulations and rules can be difficult to follow. In general, there are no federal mandates for automatic fire protection on buses, a few state requirements and a few local requirements do exist. The fact is that most of the Automatic Fire Suppression Systems are specified and installed as a conscientious effort by the owners or operators to protect their passengers and property.

The US has four distinct bus types:
- Transit
- Coach
- School Bus
- Paratransit

Each one of these bus types has different operating characteristics, different engine compartment geometry, different engine locations (front and rear) and different passenger types and capacity. Each one of these can have an effect on the type of fire and the type of automatic fire suppression system required.

The transit and paratransit market have been installing Automatic Fire Suppression Systems for more than 15 years. Currently 70 percent of the top 100 operators are specifying Automatic Fire Suppression Systems on new buses.

In 2004, the U.S. coach manufacturers voluntarily began installing automatic fire suppression systems on new motor coaches. This was prior to the Wilmer Texas incident that occurred on a 1998 model bus. As coaches come under federal guidelines, any requirements or regulations would come from the U.S. Department of Transportation (DOT) or one of its offices.

In 2005, there were 23 fatalities from a bus fire that occurred during the Hurricane Rita evacuation.
National Transportation and Safety Board (NTSB), which is charged with investigating transportation accidents, held a public hearing in August of 2006, followed by an official accident report in 2007.

The Department of Transportation released its Motor Coach Safety Action Plan in November 2009. One of the action items identified was for the NTSB to “evaluate the need for regulations requiring the installation of fire detection and protection systems”.

Several bills promoting fire protection were introduced, including bills by U.S. Representative Bill Shuster (R-PA) and U.S. Senator Kay Bailey Hutchison (R-TX). Shuster’s legislation was merged with the Motorcoach Enhanced Safety Act of 2012, companion legislation offered by Senator Hutchison, and was included as part of the Moving Ahead for Progress in the 21st Century (MAP-21) Act. The Act, which has been signed into law by the President, includes safety research initiatives for improved fire extinguishers. The research and testing shall be completed within two years, and any rulemaking shall be completed within two years after the research and testing.

The school bus market has used automatic fire suppression systems in limited quantities for at least 10 years. Most of the focus is on wheelchair lift equipped vehicles due to the longer evacuation times. Several states (Georgia, Virginia, New York, New Jersey, and Florida) have regulations in place or are considering them.

**Why you should consider an Automatic Fire Suppression System**

The influencing factors for installing an automatic fire suppression system are varied. With very few regulations mandating their use, most decisions are voluntary, although perhaps influenced by media coverage, passenger complaints or financial losses.

The reasons to install an automatic fire suppression system should simply be because they can effectively detect fires and suppress fires while providing enough time to safely evacuate all of the passengers, as well as minimize damage to the vehicle.

The reasons used not to install a system range from system and life cycle costs, to questions on effectiveness, false alarms, and cleanup.

If you are looking for a low cost, bolt-in solution that claims to put out all fires with no cleanup and no maintenance, it simply does not exist.

In reality, the fire protection engineer must be able to balance the price target the customer wishes to stay within, along with the performance the customer wishes to achieve. Sometimes, a low initial system cost may mean a high life cycle cost. (For instance, if a component must be replaced one or more times during the life of the bus, this needs to be taken into account.) When contemplating a system, the following should be considered:

- System Cost
- Installation
- Maintenance
Automatic Fire Suppression Systems typically consist of the following key components:

- Fire Detection
- Fire Suppression
- Driver Display and/or Control System
- Interface with Vehicle

**Fire Detection**

Early detection limits the size and intensity of the fires, which reduces the risk of spreading and igniting Class A materials, but also increases the effectiveness of the fire suppressant agent. However, there can be an inverse relationship between the speed of a sensor and its susceptibility to false alarms. Sensors that are very fast in detecting can also be subject to higher false alarms, if not designed and installed properly.

Each of the available sensors is designed to detect a specific type of event and the fire signature that is being produced by the event (i.e. Smoke, Heat, and Flame).

Everyone is familiar with smoke detectors, so we will use this as an example. You see them in homes, offices, public buildings, ships, etc. Since they are designed to alarm in the early stages of a fire, before flames typically occur, they can be very fast and effective. If you have ever set off your smoke alarm off because you left the popcorn in the microwave oven too long, you have experienced what is called a false alarm. The good news is, you can open a window, fan the smoke detectors and laugh about it. If a false alarm occurs on a bus, the system will discharge the fire suppressant agent, the bus will stop and all of the passengers will be evacuated off of the bus. Trust me, there won’t be a lot of people laughing and there will be some monetary expense incurred.

Just using the smoke detector as an example, let’s see what false alarm sources the bus may have present in the engine compartment. The engine burns fuel which produces the same by-products as a fire. Any exhaust gases produced by the bus, or other vehicles in the vicinity, have the potential to cause a false alarm. These are not the only false alarm sources, but we will stop at this one for now.

Next, let’s look at the maintenance aspect. Smoke detectors are meant to be used in fairly clean environments. This is why you see them in homes and office settings. This is not to say that they are not used in dirtier environments, but the maintenance cycle to ensure the sensor stays clean so that it can perform properly is much higher when a great deal of dirt is present.

Now let’s examine the effects of airflow on the smoke detector. In normal applications, you will see smoke detectors located in the ceiling. That’s because smoke rises and it collects on the ceiling. Now imagine if you put a high airflow fan blowing the smoke. The smoke would dissipate and not reach the sensor until the fire grows larger and produces enough smoke to fill the room and reach one of the smoke detectors. This is the same effect that occurs from the cooling fan located in the engine compartment.

Hopefully, you are starting to understand that selecting a fire detector is not as straightforward as you may have first thought.

A more thorough analysis can be found in a paper written by Paul Smith and Adam Chattaway, “A Comparison of Various Fire Detection Methodologies in Transit Vehicle Fire Protection Systems.” (also included in your information.)
FIRE SUPPRESSION

After we have selected the appropriate fire detectors, we must then decide which type of fire suppression agent will be best suited for the environment. The more commonly available agents are dry chemical, gaseous and watermist. Like detection systems, each agent has its tradeoffs. Many of you may remember a gaseous agent called Halon 1301. It was very effective and required no cleanup. However, the fact that Halon 1301 was deemed to deplete the ozone layer, the U.S. banned production of the product in 1994.

When selecting a suppression agent, the top criteria should be performance. But performance is based on many factors just like detection. In fact, some of the same issues, such as airflow, not only affect detection, but also the suppression agents. The following are a few of the concerns you need to consider:

Environmental/Health Concerns

Environmental issues don’t just include gaseous agents that may affect the atmosphere. This also includes agents that come in contact with dirty engines or that can be washed into water systems. Some agents produce by-products when they are exposed to fires or high temperatures that can be hazardous to personnel. Each country is different, so be sure to check your specific requirements.

Airflow and Engine Geometry

The amount of airflow in the engine compartment, the number and size of openings, and the amount of clutter can have an enormous impact on a particular agent’s performance. Gaseous agents typically rely on achieving and sustaining a given concentration of gas in the hazard for a given period of time. A high airflow can prevent the agent from achieving and sustaining the concentration necessary to suppress the fire and keep it from reigniting. In all cases, the agent must reach the fire in order to be effective, so the amount of clutter and blockage can result in more nozzles to ensure the agent reaches the fire.

VEHICLE INTERFACE/Driver Notification

One of the most overlooked components is the vehicle interface that performs automatic shutdown of cooling fans, fuel sources and the engine. Some are concerned about vehicles being shutdown in tunnels, or on busy roadways or intersections. Others are concerned about the driver losing steering, braking or other critical functions needed to stop the vehicle safely. Most systems incorporate overrides and other features that can allow the vehicle to be stopped safely while systematically shutting down mechanisms that are fueling the fire or causing it to spread.

There are many options available in the form of control panels, data loggers and even systems that send text or email alerts when a fire is detected on a bus. Notification to the driver can be in the form of visual lights or symbols, audible alarms or spoken alerts. In addition, the driver can have access to other controls that allow him/her to delay the engine shutdown and extinguisher discharge, or override the system and immediately discharge the extinguisher and shutdown the engine.

Future Initiatives

If the past few years are any indication, it looks like we will see more attention to the issue of bus fires and hopefully more regulations/legislation. To date, most of the installations of fire protection systems are done on a voluntary bases. Testing against realistic live fire criteria is a must, not only to provide a fair playing field, but most importantly to ensure the operators and passengers have faith in the systems.
Initiatives in the U.S., such as the recent solicitation by National Highway Transportation Safety Administration to “develop procedures to assess technologies that prevent or delay fire penetration into the occupant compartment, in order to increase passenger evacuation time,” are encouraging.

SP’s pending certification program for fire suppression systems and planned programs for fire detection are leading the way and are the first realistic fire tests specifically designed for bus engine compartments. Their involvement with Operators, Legislators, Bus OEMs and Fire Suppression System manufacturers ensures buy-in from all parties.

Reference List

The list below contains references to reports, etc… mentioned in this paper, as well as references that may be useful when evaluating Automatic Fire Suppression Systems.

Reports

7. National Transportation Safety Board, Highway Accident Report NTSB/HAR-07/01: Motorcoach Fire on Interstate 45 during Hurricane Rita Evacuation near Wilmer, TX September 23, 2005
Motorcoach Fire Investigation and Wheel Well Fire Testing

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ABSTRACT

On September 23 of 2005 during the evacuation of the coastal areas of Texas ahead of the approaching hurricane Rita, a motorcoach caught fire while on the highway and was completely consumed by fire. This accident made national headlines due to the overall media coverage of the evacuation and tragic loss of life of 23 passengers aboard the accident motorcoach. The National Transportation Safety Board investigated this accident and also performed tests to better understand the mechanism of the fire’s initiation. As a result of the investigation the NTSB issued recommendations to the manufacturers of motorcoaches and the regulators that set vehicle performance safety standards.

Due to submission length restrictions not all of the details of the investigation and fire tests are included in this paper. Additional information can be found on the NTSB web site or by request. Full text of NTSB accident report: HTTP://WWW.NTSB.GOV/DOCLIB/REPORTS/2007/HAR0701.PDF

KEYWORDS: Motorcoach, Tire, Fire, Investigation

INTRODUCTION

On September 23, 2005 at about 6:07 a.m. (CDT), a 1998 MCI 54-passerger motorcoach was traveling northbound on Interstate Highway 45 (I-45) with 44 passengers and the driver, evacuating in anticipation of Hurricane Rita. The passengers were from an assisted living facility in Bellaire, Texas, and most needed to be carried or assisted onto the motorcoach by firefighters. The trip began about 2:30 p.m. on September 22, 2005. The motorcoach had been traveling over 13 hours in heavy traffic when the right rear (#3 axle) tire went flat and needed to be changed near the FM 1126 overpass in Rice, Texas. The tire left approximately 6,800 feet of tire marks before the motorcoach came to a stop. A service mechanic was summoned to assist and change the tire. The motorcoach continued north on I-45 for about 26 miles. At approximately 6:00 a.m. a motorist noticed the right rear (#3 axle) hub was glowing red/white hot. He was able to stop the motorcoach in the left traffic lane and told the driver (who did not speak English) of the danger. The motorcoach driver proceeded to pull the vehicle to the right shoulder, where he exited the bus along with a nursing staff-passenger (the trip coordinator) and two other nurse-passengers and saw flames coming from the right rear wheel well. The passengers, with help from the nursing staff on-board and other motorists, began to disembark. At 6:07 the first call was made to 911. Six nursing staff-passengers on the vehicle, a parent of one of the nursing staff, and 14 patient-passengers were able to exit the burning vehicle. Twenty-three patient-passengers, many of those who needed assistance in walking or needed to be carried off the vehicle were unable to escape.

The investigation began the day after the fire, on September 24, 2005. Very early in the investigation, it was established that the area of origin of the fire was somewhere in the rear wheel well area of the vehicle. This was based on witness accounts, photos from passersby, and news helicopter video footage. The investigative team sought to closely examine the origin area and determine the cause of the fatal fire. The motorcoach was placed on a lowboy trailer and moved from the accident site to a protected garage area at the District 3 maintenance depot the day of the accident. It was then made available for a detailed examination. Additionally, the site of the accident, and a site of a grass fire
approximately 3.2 miles south on I-45 were also examined. The following are some the observations from those examinations.

Accident Site

The accident site was located on the right shoulder of I-45N, near the Beltline road overpass (Figure 1). The road surface was stained by fire debris, and a grass fire had spread from the motorcoach east toward the service road. The concrete road surface appeared to have a localized area of spalling where the rear of the motorcoach was located during the fire. After the fire, the roadway had been cleared of debris using a skid steer type loader.

Grass Fire Site

On the day of the accident at a location approximately 3.2 miles south of the accident site (at exit 266) a grass fire occurred along the median between the northbound and southbound lanes. The fire was reported to the Ferris Volunteer Fire Department prior to the accident at 6:04am. This was just a few minutes prior to the first calls to 911 to report the motorcoach fire at 6:07am. In the middle of the burnt patch of grass, a metal object was found (Figure 2). This metal object was similar in appearance to metal objects recovered from the tag axle spindle assembly of the accident bus. After close examination it was determined that the metal object was consistent with the remaining deformed roller bearings later found in the motorcoach tag axle hub assembly.

Figure 1: Accident site location

Figure 2: Metal object found at grass fire site
Vehicle Examination

Witness statements indicated that the fire started on the passenger side tag axle tire. After inspection of the vehicle, indicators were found that supported those witness statements. The indicators were fire patterns and the degree of fire damage. The rubber, from the passenger side tag axle tire, was completely consumed by the fire. The only remnant of that tire was the non combustible steel belting lying on the steel rim. The remaining tires on the passenger side and all the tires from the driver’s side had varying amounts of rubber remaining. This suggested that the passenger side tag axle tire became involved earlier than any of the other tires. Besides the difference in the degree of consumption exhibited by the tires, there were patterns left behind which suggested the fire originated and propagated from the wheel well area. These patterns did not identify the passenger side tag axle tire in particular, but they did identify the passenger side wheel well area as the origin. These patterns were the relative lack of soot, or clean burn, above the wheel well area (Figure 3), and the fire damage propagating up and away from the wheel well. The relative lack of soot in the area above the wheel well was indicative of an intensely heated region which suggested prolonged burning in the wheel well area below. The fire damage propagating up and away from the wheel well along a continuous, combustible surface (the fiberglass body panel), indicated that the fire spread out and away from the wheel well. Considering the fire patterns, the comparative mass loss of the rubber tires and the witness statements, the fire’s origin was established as being in the passenger side rear wheel well compartment. In support of this determination were video and still images (Figure 4) showing the fire concentrated in the wheel well area before spreading to the rest of the vehicle.

![Figure 3: Clean burn area shown in circle. Fire spread shown along direction of the arrow](image1)

![Figure 4: Photo by motorist showing an early stage in the fire](image2)

The cause of the ignition was attributed to the failure of the spindle bearings in the tag axle wheel hub.
assembly on the passenger side of the vehicle. This failure caused excessive heat buildup, to the point where some of the cylindrical spindle bearings inside the wheel hub fused into a solid mass (Figure 5). The fusion temperature of the steel used in bearings is in the neighborhood of 2400°F. A witness described the hub assembly’s appearance, just prior to the accident, as being white hot. This overheated hub assembly could have provided a hot surface ignition source for the rubber tire.

![Fused TAG axle spindle bearings](image)

**Figure 5: Fused TAG axle spindle bearings**

The rate at which the rubber tire burned may have been significantly increased by the heat radiated from the glowing hub components, and from being in the confinement of the wheel well. From the initial burning tire, the fire spread to the adjacent tires, other combustible wheel well area components, and to the fiberglass exterior of the motorcoach. Besides the tires which represented the bulk of the fire load in the wheel well, there were other parts such as the air bags, bushings, and mud flaps which are also combustible. It is possible that some diesel fuel, from a preexisting fuel leak, may have gotten involved and helped spread the fire during the incipient stage. At the scene of the tire change in Rice, TX, there was a liquid spilled on the asphalt (in a pattern resulting from dripping) in the area beneath where the motor coach’s engine would have come to rest. The presence of fuel was established using chemical gas chromatography (GC) analysis of a liquid soaked asphalt sample taken from the spill area and comparison with diesel fuel drawn from the motor coach’s fuel tank. In addition to this fuel leak, there was the potential for involvement of significant amounts of diesel fuel from the fuel delivery system along the centerline trench of the vehicle in which fuel lines and other systems were routed. The fuel lines in this area were thermoplastic and they were separated from the wheel well by two small access panels made of a combustible material. One of these access panels was completely consumed during the fire and the other was partially melted and deformed. The fuel lines behind these access panels were completely consumed during the fire, from the manifold in the engine compartment all the way to approximately a foot from the fuel tank. The time at which the fuel system in this area was compromised is unknown, but due to the proximity of the access panels to the fire’s origin it is likely that the fuel could have played a significant role early in the fire’s development.

The most likely method of the initial entry for the fire into the passenger compartment was from burn through of the exterior fiberglass body paneling just above the wheel well area or by compromising the windows above (Figure 6). The panels inside the wheel well that were exposed to the roadway were lined with sheet metal that would have acted as a barrier for the fire during the early stages. By burning through the exterior fiberglass and underlying foam insulation, just above the wheel well, an opening into to the ventilation ductwork that ran along both sides of the motorcoach at floor level could have been created. This ductwork also extended up, behind the interior panel, to a vent grill just below the bottom of the window. Burn through of the exterior panel can allow the passenger cabin to begin filling with smoke and for an external fire to start spreading to interior components. The interior
components were the standard equipment of the motorcoach including any personal effects carried on by the passengers. As the fiberglass exterior continued to burn, the burn through area increased in size allowing more heat and smoke to enter the passenger compartment. The accelerating fire growth eventually led to total fire involvement throughout the vehicle.

Based on the observations from the vehicle examination, the circumstances leading up to the accident, witness statements, photos, and the fused wheel bearings, it was established that the fire originated from the overheated TAG axle wheel bearings. In order to better understand the mechanism of how the bearing failure became a tire fire, the following testing was conducted.

**Fire Testing**

Three different tests were conducted to investigate the failures and conditions, which could lead to a tire fire at the tag axle position. The failure modes were selected based on Greyhound’s own experiences with tire fires and on insight gained from previous and ongoing Safety Board investigations. The first test examined the potential for inducing a tire fire by running the tire at various levels of inflation below the operating pressure specified by the manufacturer. Two additional tests involved tag axle wheel bearing failures. The first bearing failure was induced by lack of lubrication and the second by the removal of rollers from the outer wheel bearing. The tests have captured the sequence of events leading to a tread separation and tire fires in these specific cases. In the test of the under-inflated tire, a fire did not result. In that case, the tire heated up significantly, losing its structural integrity, resulting in tread separation. Both bearing failure tests resulted in a fire. These test results expose the main heating mechanism during a bearing failure, and suggest that the strongest signature for the impending fire could be found in the brake components. These tests also provide a starting point for any future testing of tire fire causes as well as technologies to detect tire fires before they occur.

An additional outcome of this testing was to observe, first hand, the limited indicators that present themselves to the driver during the sequence of events leading to a tire fire. From the driver’s perspective, there was not any significant change in vehicle handling throughout the event. There were brief periods of noise produced by the failed bearing and also brief periods of odor resembling the smell of burning oil or rubber. Witnessing the firefighting efforts, insight was gained which
justifies the general consensus that a tire fire is persistent and will most likely reignite after having been knocked down with an extinguisher. This is due to the heated brake and wheel components, which end up in close proximity or even direct contact with the tire once the tire has blown out.

The testing was conducted at the Firestone™ Texas Proving Grounds, August the 26th and 27th 2006. Participants and witnesses to these tests included staff from Greyhound Lines, Motor Coach Industries, Federal Motor Carrier Safety Administration, Lancer Insurance, Bridgestone/Firestone, and the National Transportation Safety Board.

Test Vehicle

The vehicle used in the tests was a 2003 Motor Coach Industries (MCI), model G4500, unit #7030. The motorcoach was equipped with a “Q” brake assembly affixed to an articulating non-steering tag axle arm. The tires used as test specimens were Firestone’s model FS400 tires. The motorcoach was loaded with 16,000 lbs of sand bags to bring the vehicle slightly over GVWR (Gross Vehicle Weight Rating) simulating an extreme case of passenger and baggage load. The exterior body panels of the test vehicle were protected from the outside in the area above the wheel well by attaching sheet metal to serve as a fire resistant barrier (Figure 7). This barrier also served as a mounting point for a boom arm used to support some of the instruments and cameras used during the tests.

Instrumentation

The observations and measurements made during the tests were mainly from the use of temperature sensors and video cameras. The temperature sensors used were type K thermocouples and infrared pyrometers. The infrared pyrometers were used to monitor the temperatures of moving and rotating components where as the thermocouples were used in stationary areas. The cameras were located inboard and outboard of the wheel well and were connected to a digital video recorder (DVR) and a television monitor to be viewed in real time inside the vehicle during the tests.
Thermocouples were attached to the fender walls of the wheel well, to the top and bottom brake shoes, and free standing in the air space within the wheel well. For the brake shoes and the fender walls the thermocouples were spot welded directly on to the metal surfaces. Spot welding was accomplished by making a small divot with a prick punch at the location of attachment, inserting the thermocouple wires into the divot and then using a capacitive discharge welder to fuse the connection.

**TEST I (Under inflated tire test)**

The overall objective of this test was to investigate the temperature rise caused by under inflation of the tire, and to see if a tire fire would occur from this condition. It was desired to relate tire temperature rise to tire pressure for a constant vehicle speed of about 68 miles per hour. The testing started by first inflating the tires to the manufacturers recommended pressure and running the vehicle until a steady state temperature was reached. Upon reaching the steady state temperature, the vehicle was stopped and the pressure was reduced on the tag axle tire that was being tested and the vehicle was then driven once again until steady state temperature was reached. This procedure was repeated ten times before the tire failed. The starting pressure was 110 pounds per square inch. The pressure was reduced at each subsequent run to 106, 91, 75, 57, 50, 41, 37, 35, and 31 pounds per square inch. Measuring the temperature of the tire proved more difficult than originally anticipated due to the cooling effect of the air stream while the vehicle was in motion. This caused the skin temperature of the tire to be significantly lower than the bulk temperature of the tire. This made it difficult to establish when steady state was achieved and for this reason the interval between pressure reductions was set at four laps around the track. Each time four laps were completed the vehicle was stopped and the tire temperature was measured by a hand held pyrometer until the temperature reading would stop rising. That temperature was considered to be the actual bulk temperature of the tire.

In this test no fire resulted. The failure resulting from this test was a de-lamination, that is, the separation of the tread from the tire casing. Visually there was not much indication that the tire was under inflated until the inflation pressure reached approximately 60 pounds per square inch. At this pressure the tire had a noticeable bulging appearance at the tire/roadway contact location. At the end of each four-lap run when the temperature of the tire was measured, an overall assessment of the temperatures of the tire and wheel components was made with the hand held infrared pyrometer. It was consistently found that the portion of the tire that heats up the most is the shoulder of the tire, followed by the tread and then the sidewall. During the test runs with pressures below approximately 50 psi, the tire’s tread became soft, leaving tar like residue and small chunks of rubber on the road surface. The wheel components such as the hub, the brake drum and rim did not increase in temperature beyond normal operating levels. The temperature measured by hand held pyrometer, at the completion of each four-lap run, is shown in Figure 11.
Figure 8: Maximum tire temperatures measured using the hand held pyrometer when the vehicle was stopped

**TEST II (Low Lubrication Bearing Test)**

In this test, the sensitivity of a bearing to low lubrication and how that results in a tire fire was explored. The intent was to first run the vehicle with the correct amount of lubricant in the wheel hub cavity to obtain a baseline measurement of the wheel component temperatures. Then the lubricant level was reduced until bearing failure and a tire fire occurred. The vehicle was driven at a constant speed of about 68 miles per hour during this test. The reduction in lubricant was done in two steps. The first reduction was accomplished by removing the rubber plug in the center of the plastic hub cover. This condition could be representative of a typical in service lubricant leak. The second reduction involved removing the outer bearing and lowering the lubricant level in the hub cavity so the inner bearing would continue to be lubricated but the outer bearing would run dry. The outer bearing was wiped dry with a rag before being reinstalled. The baseline run was set at four laps around the track before the first reduction in lubricant level was done. The reduced oil level run also lasted for four laps before reducing the oil level to the dry bearing condition. The dry bearing run was conducted for approximately one and a half laps before a fire occurred.

In this test, the hub did not exhibit any noticeable temperature rise above normal when the hub cavity was partially drained of lubricant by removing the fill plug. At this level the bearing was still getting some lubrication and the operating temperature of the hub did not rise abnormally. After wiping the outer bearing dry and lowering the lubricant level such that the outer bearing would not get lubricated, the bearing quickly began to fail. The dry bearing run began at 12:41 pm and after approximately one lap around the track a high pitched squealing noise was heard inside the vehicle. The noise was coming from the tag axle area and the source was presumed to be the bearing. At about the same time, an odor resembling burning rubber or oil was noticed in the test vehicle. The noise and smell were also noticeable from inside the chase vehicle. The squealing noise lasted for approximately 20 seconds. The odor would come and go until the end of the test when the tire fire ignited. At 12:49 the vehicle was pulled over to inspect the wheel. At 13:14 the vehicle started up again and the test resumed. From the camera view of the hub, the plastic hubcap was seen to come off the wheel hub at 13:24. Also the inner oil seal of the hub was noticed to begin to leak allowing lubricant to coat the brakes. The brake shoes also appeared to excrete a resin. At 13:32, the brake shoes began to rub against the brake drum producing smoke and heat resulting in localized glowing on the bottom brake.
shoe which was accompanied by sparks. One minute later, the entire brake shoe and drum interface began to glow orange. At 13:34 the lube oil and brake shoe resin that had coated the brake shoes began to ignite producing flashes of flames. The flashing became a constant fire attached to the brake shoe and brake drum interface. The vehicle was pulled over at 13:35 and the fire was quickly knocked down using a CO2 extinguisher. The tire did not appear damaged and at 13:42 the vehicle was restarted and the test resumed. Within two minutes, the drum and brake shoe were glowing orange again and at 13:46, the lube oil fire restarted. The vehicle was driven with the fire until 13:51 when the tire blew out and the vehicle was pulled over. When the vehicle came to a stop the tire had come partially off the rim and was burning (Figure 9). Shortly after the vehicle stopped the air suspension bag also failed. The resulting tire fire was initially fought using a 20 pound carbon dioxide (CO2) extinguisher. The CO2 managed to initially knock down the fire but just a few seconds after it was knocked down it flared back up again. The fire truck that was standing by deployed a hose line and doused the tag axle wheel with water knocking the flames down again. The fire flared back up after being dowsed with water. This cycle of knock down and flare up repeated three times until the fire stopped flaring back up.

After disassembly of the wheel, the rollers of the outer bearing were found fused together (Figure 10). The inner bearing had a blackened appearance but was still able to rotate freely. The brake shoes were severely worn especially at their ends. From the temperature measurements made during the test, the highest temperatures were associated with the hub (Figure 11) and brake components (Figures 12, 13) followed by the wheel rim. The signal from the thermocouple attached to the inboard side of the brake drum was lost during the test. Judging from the orange glow of the drum, that component would have attained the highest temperature overall. The fender walls exhibited the least amount of temperature rise. The tire temperature did not rise beyond normal temperatures prior to the onset of the fire.
Figure 10: Outer bearing with fused rollers

Figure 11: Hub temperature
TEST III (Damaged Bearing Test)

This test was an attempt to represent a condition of a failed outer bearing that did not result from lack of lubrication. The hub was filled with lubricant to the appropriate level at the beginning of the test. The races (cups) of the outer bearing were installed without rollers, which simulated the bearing failure. The lack of rollers caused the wheel to rotate in a non-concentric manner about the
spindle. The wheel was kept on the spindle by the interference between the bearing races and the nut and washer on the spindle end. In this test the vehicle was run continuously at a constant speed of about 68 miles per hour until a fire occurred.

In this test, the objective was to observe the chain of events associated with a bearing failure that did not occur due to lack of lubrication. The hub cavity was filled to the manufacturers recommended level of lubricant and the outer wheel bearing was installed without the rollers in an attempt to simulate a worn or failed bearing. After the vehicle was moved only about 100 -200 feet the inner oil seal of the hub began to leak oil. This was visible from the inboard camera that was pointed at the lower brake shoe and drum interface.

The vehicle entered the test track at 19:14 and started to travel at a constant speed of about 68 miles per hour. At 19:32, a light white smoke was observed from the inboard cameras to be coming out from the brake shoe and drum interface. Within six minutes, the amount of smoke became significantly more substantial. At 19:43, a faint glowing was observed at the leading edge of the bottom brake shoe. At 19:50, there appeared to be a hot spot in the middle of the bottom brake shoe identified as a glowing point. At 20:01, the perimeter of the brake drum began to faintly glow and sparks were observed coming from brake shoe and drum interface. At 20:03, the entire perimeter of the drum was glowing orange and a continuous shower of sparks and intermittent flashes of flames were coming from the interface between the bottom brake shoe and drum. At 20:05, the drum’s glowing perimeter started to change from orange to yellow. This was accompanied by heavier smoke production, which had a darker appearance. Two minutes later, at 20:07, a fire was observed to be coming from the interface between the brake shoe and drum. This fire was constant with the exception of brief periods of approximately one-second duration where the flame would extinguish and then reignite. At 20:08, the vehicle was pulled over and a 20 pound dry chemical extinguisher was used to try and extinguish the fire. The tire had not blown out and remained securely on the wheel rim. The fire was quickly knocked down by the application of the dry chemical agent but it reignited a few seconds later. The fire was knocked down once again with the same extinguisher and did not reignite. Upon reviewing the video, it was seen that the reason for the reignition was oil dripping from the hub’s inner oil seal onto the brake shoe and glowing brake drum. After the fire was knocked down the second time, the wheel components were allowed to cool without further application of extinguishing agent. It took about ten minutes for the drum to stop visibly glowing. The vehicle then was driven back to the garage at slower speeds for a tear down of the wheel. On the way back to the garage, it was necessary to stop the vehicle twice and have the fire truck apply water to the wheel components because the temperatures of the brake shoes were rising quickly and the drum was beginning to glow again.

After disassembly of the wheel components, the spindle was found to have some scoring on its surface. The inner bearing appeared to be intact and was able to rotate freely. The inner bearing’s appearance was not blackened as was the case in Test II. Also the brake shoes did not appear to have been worn down as severely as in the previous test. From the measurements made during the test, the highest temperatures recorded were associated with the brake drum. Specifically, the inboard side of the brake drum reached approximately 1300 degrees Fahrenheit. The brake shoes registered the next highest temperatures in the order of 750 degrees Fahrenheit. The wheel rim and hub center reached temperatures of approximately 550 degrees Fahrenheit. The least significant temperature rise was that of the fender walls, which only rose in temperature when the fire occurred.

Conclusions

As a result of this investigation and testing, the Safety Board recommended that the protection of the fuel system be enhanced in vulnerable areas. The length of time available for safe egress depends on the time until smoke and heat begin to enter the passenger cabin. In order to extend this time the Safety Board recommended that the exterior of the motorcoach be fire hardened in the areas surrounding the wheel wells. In addition to the passive enhancements to the fire resistance of the vehicle, active detection and suppression systems were also recommended.
Motorcoach Tire Fires – Passenger Compartment Penetration, Tenability, Mitigation, and Material Performance

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ABSTRACT

Full-scale fire experiments were conducted at the National Institute of Standards and Technology (NIST) to investigate tire fire interactions with the passenger compartment of a motorcoach. A burner was designed to imitate the frictional heating of hub and wheel metal caused by failed axle bearings, locked brakes, or dragged blown tires. Two experiments were conducted to determine the mode of penetration of a tire fire into the passenger compartment. For the first experiment, heating to obtain tire ignition was initiated on the exterior of the right side tag axle wheel and for the second, on the exterior of the right side drive axle wheel. Three experiments were conducted to examine fire-hardening of the motorcoach against tire fire penetration. The methods explored were: (1) replacing combustible external components with metal, (2) covering combustible external components with an intumescent coating, and (3) placing a metal fire-deflector shield above the fender. A final experiment with a partially furnished interior investigated tire fire growth within the passenger compartment and the onset of untenable conditions. Measurements of interior and exterior temperatures, interior heat flux, heat release rate, toxic gases, and visibility were performed. Also, standard and infrared videos and still photographs were recorded.

The experiments showed that the tire fires ignited the plastic fender and glass-reinforced plastic (GRP) exterior side panel (below the windows) upon which the fires spread quickly and penetrated the passenger compartment by breaking the windows. Measurements showed that other potential fire penetration routes (flooring and lavatory) lagged far behind the windows in heating and degradation. Fire-hardening using steel components had the greatest effect, followed by using an intumescent coating. Tenability limits were reached within 11 min after fire penetration throughout the passenger compartment and by 7 min near the fire.

In addition to the full-scale motorcoach experiments, the flammability performance of four interior combustible motorcoach components was tested beyond the current requirements by applying flammability tests from FAA and FRA standards for comparable aircraft and train passenger car components, respectively.

KEYWORDS: Motorcoach fire, bus fire, tire fire, vehicle fire, window breakage, fire penetration, fire hardening, compartment tenability, transportation fires

INTRODUCTION

Research concerning vehicle fires is important for the prevention of life and property losses. Fires in vehicles such as motorcoaches which carry as many as 56 passengers have potential for a large number of victims and significant property losses from each incident. One such motorcoach fire occurred during the evacuation of Gulf Coast residents during Hurricane Rita in 2005 and cost the lives of twenty-three occupants. [1] This tragedy provided the impetus for the National Highway Traffic Safety Administration (NHTSA) to sponsor the National Institute of Standards and
Technology (NIST) to conduct research to support NHTSA’s current effort on improving motorcoach fire safety based on recent National Transportation Safety Board (NTSB) recommendations [1]. NIST’s research was designed to accomplish the following tasks:

- Evaluate the material flammability of actual motorcoach components through their performance against various standard flammability test methods.
- Establish an understanding of the development of a motorcoach tire fire and its subsequent spread into the passenger compartment.
- Determine the feasibility of fire-hardening or increasing fire resistance of motorcoach exterior components near the wheel well.
- Assess tenability within the passenger compartment in the event of a wheel-well fire and identify potential mitigation strategies.

Whereas motorcoach fires may result from electrical system malfunctions, engine compartment leaks, component overheating, or tire fires, this research was focused on the penetration of motorcoach tire fires into the passenger compartment, methods of fire-hardening the passenger compartment against tire fires, and untenable conditions and available time to escape for tire fires. Tire fires typically result from the frictional heating of hub and wheel metal caused by failed axle bearings, locked brakes, or dragged blown tires. [2]

For this research project, only the rear half of a motorcoach was used. Six full-scale fire experiments were performed: two passenger compartment penetration experiments, three fire-hardening experiments, and one tenability experiment which examined when conditions due to fire in the motorcoach become too severe for human survival. In order to imitate the frictional heating of hub and wheel metal, a unique burner was designed to heat the metal of the wheel without preheating the tire. In addition to the description of full-scale tire fire experiments, the final report on the project [3] includes: (1) a detailed literature review providing background on other research related to motorcoach fires and flammability test methods for materials used in transportation and (2) a description of flammability testing of motorcoach interior components using more challenging Federal Aviation Administration (FAA) and Federal Railroad Administration (FRA) requirements.

While much bus fire research has been conducted in the past, few of the efforts focused on tire fires. A recent comprehensive study on bus fire safety was conducted by the SP Technical Research Institute of Sweden [4]. For a full-scale tire fire test involving the use of a motorcoach rear wheel well, SP observed different passenger compartment penetration behavior than NIST, probably due to SP preserving the bus for future testing by putting a protective cover on the combustible exterior.

**FLAMMABILITY TESTING OF ACTUAL MOTORCOACH MATERIALS**

Flammability testing was conducted on a set of materials taken from used motorcoaches in order to assess how motorcoach materials perform beyond what is normally required by FMVSS 302 [5]. Typical interior materials were selected from seat, wall, and ceiling constructions for flammability tests since these materials constitute the bulk of the contents in the interior compartment. The materials, considered representative of what is found in motorcoaches currently in use, were obtained from two high production volume Motor Coach Industries (MCI) E-series motorcoaches (2000 model year) except for the parcel rack doors which were from 2003 to 2009 J-series models.

FMVSS 302, a corresponding European version (ECE 118 [6]), FAA, and FRA flammability tests were performed on four motorcoach interior materials: interior wall panels, parcel rack doors, seat fronts, and seat backs. The applicable fire tests found in these regulations are shown in Table 1. The selected materials were subjected to the FMVSS 302 standard to verify compliance. From the other, more stringent standards, a test procedure was utilized for a motorcoach material when the corresponding material for the same function (e.g. seat), but different application (i.e. train or airplane versus bus) would be subject to that test under the regulations for trains or airplanes.
Table 1  Material selection and appropriate flammability tests.

<table>
<thead>
<tr>
<th>Material</th>
<th>Regulations and Relevant Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat bottom and back cushion</td>
<td>Horizontal spread</td>
</tr>
<tr>
<td>Wall trim panel</td>
<td>Horizontal spread</td>
</tr>
<tr>
<td>Parcel rack door</td>
<td>Horizontal spread</td>
</tr>
<tr>
<td>Back of seat back</td>
<td>Horizontal spread</td>
</tr>
</tbody>
</table>

Of the four materials tested using FMVSS 302, only the back of the seat backrest failed by exceeding the horizontal burn rate criteria by 25%. The fact that the seat backrest was used and ten years old could have had some impact on its performance. Of the four components tested under the FAA flammability requirements (standards not required for motorcoach materials), only the interior wall panel passed. All four components failed the FRA flammability requirements (also not required for motorcoach materials). The degree to which the failure criteria were exceeded in the tests failed by the seat components and the parcel rack door indicate that these motorcoach interior materials burn significantly more easily than comparable components approved for use in aircraft and railcars.

FULL-SCALE EXPERIMENT SET-UP

The test matrix is listed in Table 2. A diagram of the rear half of the motorcoach used for all of the full-scale experiments is shown in Figure 1.

Table 2  Test matrix

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Experimental Focus</th>
<th>Axle of Heated Wheel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Passenger compartment penetration</td>
<td>Tag</td>
</tr>
<tr>
<td>2</td>
<td>Passenger compartment penetration</td>
<td>Drive</td>
</tr>
<tr>
<td>3</td>
<td>Fire-hardening, metal exterior</td>
<td>Tag</td>
</tr>
<tr>
<td>4</td>
<td>Fire-hardening, intumescent coating</td>
<td>Tag</td>
</tr>
<tr>
<td>5</td>
<td>Fire-hardening, flame deflector</td>
<td>Tag</td>
</tr>
<tr>
<td>6</td>
<td>Passenger compartment tenability</td>
<td>Tag</td>
</tr>
</tbody>
</table>

Burner

A special burner was designed and built that would focus substantial heat, (up to 100 kW) on the metal of a motorcoach wheel without the flames or exhaust gases impinging on the rubber. The purpose of this design was to cause the rubber to ignite just from heat conduction with hot metal, which qualitatively simulates the frictional heat generated from failed axle bearings, locked brakes, or dragged blown tires. Figure 2 shows photographs of the burner and shield.

The design of the burner was a 25 mm OD stainless steel (type 304) tube bent into a 30.5 cm circle with ten high output heating torch nozzles attached perpendicular to the plane of the circle. An assembly of valves and a mixing chamber for the natural gas and high-pressure air was attached to the circular tube. The flames were meant to be pre-mixed so nearly all of the heat was efficiently generated at the flames. The burner was mounted on a long, wheeled cart to enable positioning of the flame tips and fast removal of the burner after tire ignition. A tire shield was fabricated and placed between the wheel and tire to prevent direct heating of the tire by burner flames and gases. For the
second test (and subsequent tests), a calcium silicate blanket was placed on top of the shield for additional insulation to minimize radiation and convection from the shield to the tire.

**Figure 1** A drawing of the motorcoach rear half which was used for tire fire experiments. Dimensions are in meters. Distance measurement uncertainty is ± 0.3 %.

**Figure 2** (Left) A photograph showing the burner pre-mixed natural gas and air torches impinging on a tag axle wheel. (Right) A photograph showing the tire shield inside a drive axle wheel rim with an insulating cover to minimize heating from the shield to the tire.

**Measurements**

For each tire fire experiment, temperature measurements were made and recorded in the interior near the windows and on the floor, on the exterior near the windows and body panels, on the wheels and tires, and in the wheel well and axle regions. Interior heat fluxes were measured in several locations, and the total heat release rate (HRR) of the fire was calculated from the hood exhaust using oxygen depletion calorimetry. For the tenability experiment, the locations of the temperature and heat flux measurements were changed and many more locations were added. Also, combustion gases (O₂, CO₂) as well as toxic gases (CO, HCN, HCl) were measured, and visibility was analyzed. Several
standard and infrared videos and many photographs were recorded for each experiment. Figure 3 is a diagram of the measurement locations for the penetration and fire-hardening experiments.

**Penetration Experiments**

For each of the two penetration experiments (described in detail in the full report [3]), the tires were ignited by heating different wheels. For all of the experiments, the heated wheels were on the right side (when facing forward) of the motorcoach which was also the passenger entry door side and opposite the driver’s side. The first tire fire was started on the tag (rearmost, also called dead or lazy) axle, which only had one wheel and tire per side. The second experiment started on the drive axle (in front of the tag axle), which had two wheels and tires per side.

**Fire-Hardening Experiments**

Three methods of fire-hardening, to limit penetration of the passenger compartment by tire fires, were explored: (1) replacing the combustible exterior with steel, (2) covering the combustible exterior with intumescent coating, and (3) adding a flame deflector. For all of the fire-hardening experiments, the tag axle wheel was heated.

![Diagram of motorcoach showing locations of interior floor thermocouples and the locations and directions of heat flux gauges for penetration and hardening tests.](image)

The first method involved removing material which acts as fuel during a tire fire by replacing the external glass-reinforced plastic (GRP) exterior side panel below the windows and the plastic fender with sheet metal. The type of sheet metal used for the side panel and fender was 0.79 mm (22 gauge or 1/32 in thick) type 304 stainless steel. A diagram of the motorcoach with both the stainless steel panel and fender is shown in Figure 4 (upper left).

The second fire-hardening method was to cover the motorcoach exterior above the tires with an intumescent coating which put a physical barrier between the combustible materials and the tire fire plume. An intumescent coating is a polymer that swells and creates a char barrier to heat and mass transfer when heated by flame. An effective char barrier can limit pyrolysis of the combustible material underneath and prevent fuel (combustible material) vapors that are generated from escaping and burning. A used exterior GRP panel and used fender were shipped to PPG Industries Protective & Marine Coatings for application of the coating. The particular coating, PITTC-CHAR XP®, is a weather and abrasion resistant epoxy designed for marine applications. A diagram of the motorcoach with the coated panel and fender is shown in Figure 4 (upper right).
The third fire-hardening method consisted of a deflector shield located above the fender and below the exterior side panel. The deflector was designed to deflect the fire plume away from side of the motorcoach sufficiently to impede flame spread to the exterior side panel and thus delay or prevent window breakage. Application of the Fire Dynamics Simulator (FDS) [13] software was used to estimate the effect of such a shield on the tire fire plume. While wider designs had slightly larger effects on the average plume temperatures near the windows, a 15 cm width was chosen due to the combination of its plume temperature impact and less protruding profile. The shield was made with 0.79 mm (22 gauge or 1/32 in thick) type 304 stainless steel. The deflector was 15 cm wide and protruded from the side of the motorcoach at a 45° angle above horizontal. A diagram of the motorcoach with the deflector between the panel and fender is shown in Figure 4 (bottom).

**Tenability Experiment**

A final experiment was conducted to investigate the fire growth within the passenger compartment after penetration by a tire fire and to determine the onset of untenable conditions due to the cumulative effects of heat and toxic gases. For the tenability experiment, a complete interior motorcoach volume with the same dimensions was necessary in order to provide realistic results for temperatures, heat fluxes, toxic gas volume fractions, and the time for the passenger compartment to reach dangerous absolute or cumulative thresholds for each of these hazards. A motorcoach front half was constructed to complement the original rear and make a whole interior volume with similar dimensions to an E-series model. The constructed front of the motorcoach consisted of a wood frame structure supporting a plywood deck upon which a steel stud frame was built and to which a galvanized steel interior skin was attached. The doorway was sized to approximately match that of an MCI E-series model. Stairs were built to allow easy access for instrumenting the interior and also to approximate the footprint of the original stairwell. Figure 5 (top) is a photograph of the exterior of the complete motorcoach assembly and Figure 5 (bottom) is a diagram showing the measurement layout.

For the tenability experiment, it was necessary to provide a representative and realistic fuel (combustible material) load that would ignite and become a substantial fire within the motorcoach after penetration of the tire fire through the windows. The amount of interior furnishings reinstalled was estimated to be sufficient to bring the fire in the rear of the motorcoach to flashover conditions.
(all combustibles ignite) which would provide sufficient heat and smoke spread throughout the motorcoach without risking damage to the experimental facility or danger to the research personnel. Reinstalled, original furnishings included: three pairs of seats positioned on the right side over the rear axles, a parcel rack with doors along the right side of the entire original rear half, the interior wall trim on both sides, the foam rubber window post covers, and the right side window curtain rods and screens (rolled up). The seats were installed with the original spacing in positions corresponding to the second to last row and the next two rows in front of it. This centered the three pairs of seats in the anticipated fire breakthrough area. The parcel rack was installed close to its original position.

![Figure 6](image)

**Figure 6** (Top) Photograph showing the assembly of the original motorcoach rear half and added front. (Bottom) Diagram showing the layout of measurements for the tenability test.

**RESULTS**

**Penetration Experiments**

Both experiments initiated on each axle showed penetration of the fire into the passenger compartment through the long window between the axles. This finding is in contrast with research conducted by SP [4] when a non-combustible barrier was placed on the exterior above the tires, and fire penetration through the windows did not occur. Table 3 lists the duration of the main periods of interest in these experiments: the period of heating with the burner before the tire was burning steadily, and the period between burner removal and penetration of the fire into the passenger compartment. The maximum uncertainty (combined, expanded) in the times listed is approximately
± 3 s. The period between burner removal and compartment penetration was about 1.5 min shorter for the tag axle experiment than for the drive axle experiment. In these experiments, both tire fires resulted in compartment penetration by breaking through the windows. Temperatures on the floor, near the lavatory, and in the central cable tunnel showed little increase over initial temperatures indicating that the floor and lavatory were not close to providing a pathway for fire spread into the compartment. The interior heat fluxes also stayed very low until fire penetrated the windows.

Table 3 Duration of periods of heating and between heating and window penetration.

<table>
<thead>
<tr>
<th>Period</th>
<th>Duration (s) (min:s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burner heating wheel to sustained tire burning</td>
<td>Test 1 (Heated Tag Axle Wheel)</td>
</tr>
<tr>
<td>Burner removed to fire penetration of window</td>
<td>2177 (36:17)</td>
</tr>
</tbody>
</table>

Fire-Hardening Experiments

Table 4 summarizes the key periods for the 5 experiments initiated at the tag axle wheel. It is notable that the periods for heating the tag axle wheel before sustained tire burning varied widely (between 28 min and 48 min), mainly due to intermittent blowoff of some burner torches. Tests 3, 4, and 5 listed in the table were the fire-hardening experiments. The shortest duration between burner removal and window penetration (9 min 48 s) was for test 5, the deflector experiment. The longest duration (41 min 4 s) was for test 3, the steel fender/panel experiment, although this experiment was stopped (through fire suppression) before window penetration occurred after 600 °C temperatures were measured behind the panel which threatened to ignite the paper-covered foam wall insulation. Test 4, the experiment using the intumescent coating for the panel and fender, exhibited a duration from burner removal to window penetration of 32 min 26 s. Throughout the experiment, the coating remained intact over much of the fender and nearly all of the panel, but along the bottom edge of the fender, the coating degraded sufficiently to allow some flame spread upward over the fender.

Table 4 Duration of periods of heating and between heating and penetration for the tag axle experiments with and without fire-hardening.

<table>
<thead>
<tr>
<th>Test Details</th>
<th>Test Number</th>
<th>1</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axle of Heated Wheel</td>
<td>Tag</td>
<td>Tag</td>
<td>Tag</td>
<td></td>
<td>Tag</td>
<td>Tag</td>
</tr>
<tr>
<td>Fire-hardening/Protection</td>
<td>None</td>
<td>Metal</td>
<td>Coating</td>
<td>Deflector</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Period</td>
<td>Duration (s) (min:s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burner heating wheel to sustained tire burning</td>
<td>2177</td>
<td>1705</td>
<td>2848</td>
<td>2015</td>
<td>2210</td>
<td></td>
</tr>
<tr>
<td>Burner removed to fire penetration of window</td>
<td>280</td>
<td>41:04</td>
<td>1946</td>
<td>588</td>
<td>679</td>
<td></td>
</tr>
</tbody>
</table>

*This test was stopped to prevent damage due to 600 °C temperatures behind the side panel and not fire penetration.

Tenability Experiment

The burner heating times required to generate sustained tire fires for the tenability experiment and the first tag axle penetration experiment were very similar. The time for penetration for the tenability experiment was significantly longer (6 min 39 s) than for the first tag axle experiment. Only after flames penetrated the window during the tenability experiment could the interior materials ignite. It still took nearly 2 min after window penetration for the seats to ignite. After the seats ignited, fire growth was gradual over the next 7 min until the final 2 min (prior to suppression) when the fire
growth, temperatures, and toxic gases ramped up quickly. Extinguishment was initiated when the HRR approached 6 MW which was considered potentially unsafe for the facility.

The ISO 13571 [14] standard provides guidance for calculating incapacitation and time for escape from the life-threatening components of fires. It was used to analyze the thermal and chemical species volume fraction data from the tenability experiment. The standard uses fractional effective dose (FED) and fractional effective concentration (FEC) analyses. FED is the ratio of the exposure dose for an asphyxiant toxicant to that exposure dose of the asphyxiant expected to produce a specified effect on an exposed subject of average susceptibility. FEC is the ratio of the concentration of an irritant to that expected to produce a specified effect on an exposed subject of average susceptibility. Thermal phenomena such as high temperature convective heat transfer and radiative heat flux are treated as asphyxiant toxicants and use the same FED definition as toxic gases. The specified effect is usually incapacitation which would prevent escape; death would typically follow. A detailed analysis of the thermal and hazardous gas exposures is included in the final report [3].

Table 5 lists the various hazardous conditions that were measured during the tenability experiment and the corresponding times for untenable levels to be reached from the time of fire penetration. The calculations for accumulated doses in the ISO standard have uncertainties of up to 50% which in turn impact these results for time to untenable conditions. For the rear and middle locations, the thermal hazards reached untenable levels earlier than the other hazards. For the front location, heat flux was not measured, but the time for convective untenable conditions was comparable to those for gaseous hazards. Adding heat flux to the front location analysis could put thermal conditions as the leading hazard there, similarly to the other locations, or HCl may have been the fastest hazard at the front to reach an untenable level. Of the toxicity, asphyxiation, and irritant hazards, HCl led the others to untenable conditions by over 1.5 min. Oxygen vitiation was the last hazard to reach untenable levels. All of these hazards would normally act synergistically which would cause incapacitation leading to death earlier than any single component alone.

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Time from Fire Penetration to Untenable Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Location: Rear</td>
</tr>
<tr>
<td>Radiative (heat flux)</td>
<td>511 (8:31)</td>
</tr>
<tr>
<td>Convective (temperature) fully clothed</td>
<td>641 (10:41)</td>
</tr>
<tr>
<td>Convective (temperature) lightly clothed</td>
<td>595 (9:55)</td>
</tr>
<tr>
<td>Combined radiative and convective (fully clothed)</td>
<td>503 (8:23)</td>
</tr>
<tr>
<td>Combined radiative and convective (lightly clothed)</td>
<td>485 (8:05)</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>637 (10:37)</td>
</tr>
<tr>
<td>Hydrogen cyanide (HCN)</td>
<td>627 (10:27)</td>
</tr>
<tr>
<td>Combined CO and HCN</td>
<td>619 (10:19)</td>
</tr>
<tr>
<td>Hydrogen chloride (HCl)</td>
<td>531 (8:51)</td>
</tr>
<tr>
<td>Oxygen vitiation</td>
<td>642 (10:42)</td>
</tr>
</tbody>
</table>

^b Levels assumed at locations (middle and front) other than where measured (rear).

SUMMARY OF FINDINGS AND CONCLUSIONS

Material Flammability Testing

While there may be a significant number of combinations of manufacturer, model, age, and
component design, the performance of these components is considered representative of what is found in motorcoaches currently in use. Based on the flammability test results, the following are the findings and the conclusions which can be drawn:

- One interior material, the back of the seat backrest, failed the FMVSS 302 requirement by exceeding the permitted horizontal burn rate by 25%.
- Other than the interior wall panel, all of the other components (parcel rack doors, seat fronts, and seat backs) failed the Federal Aviation Administration (FAA) flammability requirements.
- All of the components tested failed the Federal Railroad Administration (FRA) flammability requirements.
- The poor flammability test performance of the seat components and the parcel rack door showed that they burn significantly more easily than comparable components approved for use in aircraft and railcars.
- The seats and the parcel rack doors were the first interior components involved in the tenability tire fire experiment, and they constitute a majority of the combustible interior mass. Improved flammability performance of these items may significantly increase time for fire spread and untenable conditions once a fire penetrates into the passenger compartment of a motorcoach. This research was not able to examine the relationship between improved material flammability performance and fire spread within the passenger compartment.

Penetration Experiments

Based on this specific motorcoach and the conditions of these particular experiments, the following are the findings and the conclusions which can be drawn:

- Tire fire penetration into the passenger compartment occurred from flame impingement on windows and the resulting glass breakage. This finding is in contrast with research conducted by SP [4] (on a different model motorcoach) when a non-combustible barrier was placed on the exterior above the tires and fire penetration through the windows did not occur.
- A tire fire can spread to combustible exterior fenders or panels within 2 min of a sustained fire on the tire.
- The time between the start of a self-sustained or established tire fire and window breakage by fire can be less than 5 min.
- The slow rates of rise of floor and central tunnel temperatures indicate that the floor, lavatory, and central tunnel are protected sufficiently for this particular motorcoach and are not likely pathways for passenger compartment penetration in the early stages of a tire fire (i.e., prior to or immediately following window penetration).
- For the drive axle experiment, based on the rates of temperature increase observed before extinguishment, there is a possibility of an initial tire fire crossing the motorcoach by way of the drive axle within several minutes of fire penetration through the window. Window penetration on the second side would lag behind that on the primary side by the delay of the spread of fire across the axle. The tag axle experiment did not show significant heating along either axle at the center of the motorcoach or on the driver’s side.
- Temperatures in the wheel well and along the axles were sufficiently high so as to have the potential to ignite or damage any combustible materials underneath the motorcoach, but the floor and interior areas near the fire were protected by stainless steel sheet metal and a layer of insulation. Additional penetration points could occur from local degradation of less protected areas, but this was not observed for the conditions experienced in these tests with the design of this particular motorcoach.
- There was a wide range of timing for window penetration as demonstrated by the first tag axle experiment which experienced penetration in less than 5 min and the tenability tag axle experiment which experienced penetration in over 11 min. It is not known why the penetration times are different. Possible reasons include: variation in the wheel burner heating which could have caused different initial fire conditions for the two tire fires, variation in window strength and performance, and natural variation in how the plumes interacted with the windows.
**Fire-hardening Experiments**

Based on this specific motorcoach, the conditions of these particular experiments, and the particular protective designs which were attempted, the following are the findings and the conclusions which can be drawn:

- Of the three fire-hardening methods examined here, two (replacing exterior combustible components with metal or coating existing combustible panels with intumescent materials) appear to be effective approaches to improving fire safety for wheel-well fires.
- Replacing the combustible exterior side components directly over the tires with sheet metal was the most effective design for preventing the tire fire from penetrating through the windows. For the conditions tested here, it prevented penetration, but materials behind the replacement panels approached temperatures which may have led to interior ignition and flame spread. Fire penetration was delayed approximately 30 min before the test was terminated compared to the tag axle experiments without fire-hardening.
- The intumescent coating on the combustible exterior side components near the tires was the second most effective design for preventing the tire fire from penetrating through the windows. Fire penetration did occur, but it was delayed approximately 20 min compared to the tag axle experiments without fire-hardening.
- A steel deflector shield had an indeterminate effectiveness on preventing the tire fire from penetrating through the windows. The penetration time was 5 min longer than one tag axle experiment, but was 1.5 min shorter than that for the tenability tag axle experiment. Larger deflector designs that push the fire plume further from the windows could be more effective, but could create other issues related to practical implementation.
- The ABS sensor as deployed for these experiments did not respond to heating from the adjacent wheel and hub metal consistently or sufficiently to provide an effective signal of an approaching or occurring tire fire; however, a simple temperature measurement device such as a thermocouple located near the wheel could provide early warning of adverse heating in the vicinity well before tire ignition temperatures are reached.

**Tenability Experiment**

Based on this specific motorcoach, the design of its extension, the open door and fuel loading configurations, and the conditions of these particular experiments, the following are the findings and the conclusions which can be drawn:

- Thermally untenable conditions were reached at both the rear and middle measurement stations of the motorcoach by about 8 min after fire penetration with local areas in the rear near the seats untenable in less than 6 min after fire penetration. The front of the motorcoach became thermally untenable by about 11 min.
- Assuming smoke layer uniformity, carbon monoxide and hydrogen cyanide combined to make conditions untenable throughout the motorcoach just over 11 min after fire penetration.
- Assuming smoke layer uniformity, hydrogen chloride caused untenable conditions in the rear of the motorcoach at just under 9 min after fire penetration.
- Oxygen vitiation caused untenable conditions throughout the motorcoach by 11 min after fire penetration.
- Thermal conditions were generally more severe at earlier times than toxic, irritant, or asphyxiant gas conditions.
- Combination of the incapacitating effects of thermal and toxic gas effects would shorten tenability time and time to escape.
- Visibility conditions (evaluated 1.5 m from the floor) deteriorated significantly prior to fire penetration of the motorcoach. Within 30 s after penetration, visibility decreased to less than 2 m. Poor visibility could have made egress from this motorcoach difficult several minutes before conditions became untenable.
- The combination of three pairs of seats and partial trim installation was sufficient fuel loading...
to cause flashover (bring to 600 °C and 20 kW/m2) in the rear half of the passenger compartment in less than 11 min after fire penetration.

- Untenable conditions for this experiment were attained with a limited fuel loading suggesting that the conditions and timing observed in this experiment were not the most conservative.

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Disclaimer: Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is the best available for the purpose.

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REFERENCES

Examples of bus fire investigations

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ABSTRACT

Technical defects often turn out as causes for vehicle fires. This is also true for bus fires. The paper presents the analysis and results of five bus fire investigations. All fires were definitely caused by technical defects and the fires started while the buses were driving. The fires led to different damage patterns and losses. The first example presents a fire that started in the luggage compartment, an area not directly visible by the driver or the passengers. Four examples show an ignition in the engine compartment, triggered by various causes. The causes range from electrical defects or mechanical defects to bad maintenance/repair work. One of the buses burnt down completely, one was severely damaged in the engine and passenger compartment.

By investigating the situations directly before the ignition the results allow to draw conclusions from the ignitions’ causes and the whole damages about the fire propagation. This allows a risk assessment for the vehicles and the passengers. The main focus of the paper concentrates on the technical aspects leading to the fires. The selected examples illustrate the different kinds of defects resulting in an ignition, the different chronological sequences of the fire spread, and consequential risks for the occupants. Additionally the bus drivers’ descriptions about how they recognised the fires are included. The target of the paper is to contribute to the discussion about automatic fire detection and fire extinguishing systems.

KEYWORDS: bus fire, fire investigation, ignition causes, fire protection, technical defects

INTRODUCTION

A statistical collection of reliable data regarding bus fires is not available for most European countries. If data is available often it is not comparable directly and requires a wide experience about the sources and the limitations [1]. Data is available from the Scandinavian countries Norway and Sweden [2]. In the USA data is collected and published by the National Fire Protection Association NFPA [3]. Valuable information is also provided by the US-American motor vehicle research institute [4] and within the SAE Special Publications of the sessions organised by the SAE Fire Safety Committee [5].

Often fires in buses are very spectacular. If they involve injury to persons the public interest is enormous. Accordingly is the presence in the media. The fire safety of buses is hence a topic popping up in more or less regular intervals. Single events like the bus fires in Hanover, Germany in 2008 or nearby Dallas, USA in 2005 result in politicians, yellow press journalists and lobbyists calling for harder regulations and better inspections. This carries the risk, that single events are used as a basis for the development of “countermeasures”. The real risks remain not investigated and the bus manufacturers and operators are obliged to undertake measures with only small effects. On the other hand such single events can help to faster introduce regulations derived from large field studies, as seen after the Hanover fire. Based on field studies like [6] and [7] it was possible to introduce helpful and practical directives for the European market [8].
BASIC FIRE INVESTIGATIONS

After fire incidents with buses different parties are usually interested in the fires’ causes. Insurance companies want to know if they can subrogate against the manufacturer or a garage, the bus manufacturers need the investigation results to optimise their products and to minimise causes of defects. The operators need the information to make the insurances pay. If the fires led to personal injury the results are also of interest for the law enforcement agencies and courts.

Thus the quality of the investigations requires a high level. Standards like the American NFPA 921: Guide for Fire and Explosion Investigations [9] are not common in Europe. The legal experts in Europe are usually trained by their companies or by certified institutes. A background as an automotive expert is very helpful.

Nevertheless, the basic approach in automotive fire investigation is usually the same: a process of elimination. All vehicle components and systems that principally can start a fire are examined for ignition related characteristics. If no signs for an ignition are found, the component can be excluded as the cause of fire. Using the combustion triangle with its components combustible – oxidant – source of ignition the focal points are the combustible and the source of ignition. The oxidant oxygen is provided by the surrounding air. A fire can only start when the constructional separation of those components is removed by technical defect or manipulation. It is the investigator’s task to find out the reason for the failure of the separation.

CASE EXAMPLES

Several bus fire cases have been investigated extensively in different studies. Apart from [6] and [7] the American National Transportation Safety Board NTSB published well-funded investigation reports [10]. The results can be used to develop new safety standards and protection equipment.

The five cases presented below have been investigated by the main author of this paper within the last years. They were chosen for this paper because they hold typical features as seen in many other cases investigated in the same period. Together with other investigations, they can help to determine the most effective approaches for fire-safety improvements.

Example 1: Electric defect in the luggage compartment

A 2006 Daimler O350 (857) with a mileage of 244,676 km was riding in a town. No passengers were on board. After starting at a traffic light and changing up to the second gear the engine stopped running. A restart was not possible. All instruments in the dashboard did not work, neither did the emergency flasher. After leaving the bus to position the warning triangle the driver realized slightly smoke inside the rear area of the passenger compartment. No smoke was visible outside the bus at this time. After pressing the main disconnect switch of the electric system in the luggage compartment the smoke formation did not stop inside the bus. Smoke became visible at the rearmost luggage compartment’s lid on the right side of the bus. The driver opened the lid and located flames in the ceiling area of the compartment. He was able to extinguish the flames with the buses fire extinguisher.

The fire damage was confined to the luggage compartment behind the rear axle on the right side of the bus. The electric cables and the covering parts showed severe scorch marks. The passenger compartment was contaminated with soot; scorch marks were limited to the area around a floor mounted maintenance lid.

Investigating the systems and components mounted in the luggage compartment, traces of melted copper were found at an iron holder of a heating tube. Corresponding cables with traces of a short circuit were found in the area: a 4 mm² cable of the engine electronics’ power supply and a 2.5 mm² ground cable. The insulation of the energising current cable of the 3-phase alternator was melted off. This was caused by an overload of that cable. The damage pattern reached to the heating tube holder.
Due to the defective fixation the cables were in permanent contact with the holder. Through the relative movement of the components induced by the movement of the bus the insulation was worn off. The contact between the no longer insulated cable and the holder resulted in a short circuit leading to the fire. The short-circuit current led to the overloading of the energising current cable. There were no marks of the fire inside the engine compartment.

According to the operator’s and garage’s maintenance documentations there was no work carried out within this area. The degree of damage did not allow a statement whether the cables were mounted incorrectly or the plastic cable holders failed due to aging and vibration.

In the beginning it was not possible for the driver to recognise the fire by visible smoke or flames. The burning area was encapsulated and screened from the passenger compartment and the buses’ outside. Between ignition and recognition approximately 10 to 15 minutes elapsed. The repair costs were calculated to 73,500 Euros.

**Figure 1** Smoke marks above the rear luggage compartment’s lid. No traces of the fire inside the engine compartment.

**Figure 2** Fire damaged luggage compartment and detailed view on the area of the ignition.

**Figure 3** Area of ignition after demounting of the covering parts and heating tube holder.
Example 2: Mechanical defect in the engine compartment

A 2008 Neoplan PB1 / N1122-3C double-decker bus with a mileage of 530,861 km was riding on a long distance trip. Passengers were on board. The driver’s attention was called by other drivers signalising him to stop. They had seen smoke at the rear of the bus. Simultaneously the second driver, sitting at a table in the lower deck, caught the smell of smoke. After stopping and evacuating the bus the drivers and others extinguished the fire in the engine compartment with several fire extinguishers.

The fire damage was limited to the right side of the rear part of the bus. The rear side, the rear bumper and the engine compartment’s lid showed black marks and fused surfaces. The luggage compartments and the passenger compartment were neither affected by fire nor smoke. The main damages were located in the rearmost part of the right side of the engine compartment. All insulations, wires, hoses and tubes were damaged by the fire here. From the backside a typical fire cone was visible. The electric generator #3 was located in the beginning of the cone. The generator’s housing and the drive belt showed fire marks and effects of high temperatures.

The generator was dismounted for inspection. The bearing was heavily damaged. The generator’s shaft was deformed, some balls were pulverised. The friction caused by that damage heated up the generator and the surrounding areas. The resulting overload led to a jamming of the generator. The drive belt powered by the crankshaft wheel kept on running, rubbing over the jammed generator wheel. The emitted heat ignited settled dust soaked with oil. Before jamming the generator had produced enough heat for the surrounding materials to keep burning after the initial ignition.

According to the operator the air conditioning of the bus had been repaired two weeks prior to the fire. The air conditioning compressor’s damages were clearly caused by the fire and not the cause of it. The driver could not see the smoke coming from behind the bus. To make things worse the bus was driving at night. Between ignition and recognition approximately 10 to 15 minutes elapsed. The repair costs were calculated to 130,000 Euros.
Figure 6  Damages at the rear end of the double-decker bus.

Figure 7  Fire damage was limited to the right side of the rear end of the engine compartment.

Figure 8  Main damage in the lower part of the engine compartment and location of the electric generator #3.

Figure 9  Dismounted generator with heat marks and detail of the deformed shaft.
Example 3: Electric defect in the engine compartment

A 2006 Volvo 7700 city bus with a mileage of 320,000 km was riding in a town. Passengers were on board. A rear seat passenger informed the driver of strong smell of burning in the rear part of the passenger compartment. Looking in the rear view mirror the driver could see some smoke in the engine area. He stopped the vehicle at the next opportunity. After evacuating the bus he saw flames and smoke in the rear upper area of the bus. After opening the lid flames became visible in the right part of the engine. He tried to extinguish the fire with the fire extinguisher of the bus, but he failed. The fire brigade arrived in less than 10 minutes and extinguished the fire. The bus was equipped with a fire detection system.

The bus was severely damaged by the fire at the rear right corner, the rear window and on the rear part of the roof. Scorch marks were also visible on the last row of the seats and on the ceiling. The rear window was destroyed by the fire. The passenger compartment was contaminated with soot.

When investigating the damages in the engine compartment the main focus could quickly be laid on the right side. The burn pattern clearly indicated an ignition in that area. Important parts of the vehicles electric system were mounted here, including the fuse box. This was destroyed completely, only the blank was left over. All cable insulations were burnt away completely. Analysing the various components a cable ring lug showed traces of a short circuit. It was mounted incorrectly. To validate the finding the ring lug was analysed with a scanning electron microscope for the application of other materials.

Shortly before the fire the bus had been maintained in a garage and extensive maintenance work was carried out in the area of the fire’s origin. A safety check of similar buses owned by the same operator following the investigation resulted in 19 noticeable problems in 35 buses in the fuse box. In all cases the screw connections were defective.

The fire was detected by the smell from a passenger in the rear area of the bus. At this point it was not possible for the driver to detect the fire. It was not possible to estimate the duration between ignition and recognition. The remarkable point in this case is: the bus was equipped with an automatic fire detection system built in by the manufacturer himself. The detection system is based on three sensors: one located on the starter, one in the area of the turbo-charger/exhaust system and one above the generator. The thermal detectors are calibrated to a response temperature of 110° C. They are all located on the left side of the engine and thus beyond the area of ignition.
Figure 11  Damages at the rear side of the bus with focus on the right side.

Figure 12  Damage of the rear seats and the engine compartment with the main damage on the right side.

Figure 13  Location of the fuse box and electric connections.

Figure 14  Defective electric connection and melting patterns of an electric circuit.
Example 4: Turbo-charger failure

A 2008 EvoBus O510 Tourino with a mileage of 60,000 km was riding on an autobahn. Passengers were on board. The driver became aware of a reduced engine power while driving. The bus slowed down. The driver left the Autobahn as planned at the next exit and continued the trip. Shortly thereafter the driver’s attention was called by a passenger telling him of a strange smell in the rear part of the bus. A few minutes later the driver recognised smoke at the right side of the bus. He brought the bus to a stop several 100 metres later. Getting off the bus he saw flames at the right rear end of the bus. The attempts to extinguish the fire with the onboard fire extinguisher failed. All remaining passengers left the bus through the front door, no one was injured. The fire was described as spreading very fast, starting at the right rear end and entering into the passenger compartment. The arriving fire brigade extinguished the fire. The burning time is estimated to 15 to 20 minutes.

The fire progressed from the lower right part of the engine compartment over the whole back of the bus and entered the passenger compartment through the rear window. The passenger compartment’s ceiling and several seat rests showed scorch marks, the whole compartment was severely contaminated with soot.

In investigation the area of ignition could be located in the lower right part of the engine compartment. In this area the muffler of the exhaust system is mounted. The muffler is accessed via a lid on the right side of the bus. This is also the area where the first flames were seen by the driver. Nevertheless the scorch marks are limited here. This can be explained with the air flow while driving, the lack of combustibles in this area and the stack effect through the engine compartment. The heat was transported to the rear end of the bus into the lower right area of the engine. Combustibles like oil-soaked noise absorbers and dust were ignited and accelerated the fire spread.

Disassembling the muffler showed that the monoliths were broken and showed scorch marks. They were shifted towards the tail pipe. Parts of the honeycomb structure were broken off and the ceramics showed fused surfaces. Larger amounts of oil residues were found in the tubes between the turbo-charger and the muffler. As a consequence the externally undamaged turbo-charger was disassembled. The turbo-charger’s shaft was broken, the turbine wheel was lying loose in the casing. The blades were grinded radial.

The damage of the turbo-charger allowed engine oil to get into the muffler. The high temperatures led to an ignition of the oil, an increase of the temperature and the damage of the monoliths. The heat protection shield surrounding the muffler could not withstand the generated high temperatures, the protected components lying behind ignited.

The interesting point in this case is the distance between the actual cause of the fire (turbo-charger failure) and the area of ignition (muffler). This shows that searching for the point of ignition within the fire investigation does not automatically lead to the cause of ignition. The cause of the turbo-charger failure was not of interest for the customer and thus was not investigated.
The loss of engine power was no reason for the driver to stop the bus as soon as possible. Once more the information from of a passenger of an unfamiliar smell led to the discovery of the fire. The visible smoke was the reason for the driver to stop.

The temporary fast spreading of the fire could be connected to the melting of the servo-oil container.

Figure 16  Burning bus with the area of the fire’s origin already being extinguished with a fire extinguisher (red circle) and the fire brigade at work.

Figure 17  Main focus of the damage in the rear lower right corner.

Figure 18  Smoke in the passenger compartment, flames in the rear part, and the resulting damage.

Figure 19  Severe damages in the right part of the engine compartment and the starting point of the fire at the muffler (top of the right picture).
Example 5: Broken injection line

A 2007 EvoBus Tourismo RHD-M/2A with a mileage of about 320,000 km was riding on an autobahn. Passengers were on board; the vehicle was riding for 4 to 5 hours. According to the driver there were no noticeable problems like a loss in engine power, flashing warning lights or any other malfunctions. The first recognisable sign of the fire was slight smoke emitted from an area about 1 m behind the rear axle on the left side. The bus was stopped on the emergency lane and all passengers were requested to leave the bus immediately. After evacuating the vehicle the driver tried to extinguish the fire with the on board fire extinguisher. The attempts were unsuccessful. The driver stated that, after opening the rear lid, the rear left part of the engine was on fire and emitting large amounts of dark smoke. The fire brigade arrived after about 10 to 15 minutes.

Starting in the engine compartment the fire spread very fast. The bus was completely destroyed by the fire. The analyses of the burn pattern indicated the start of the fire in the engine compartment. Partly destroyed components like the cooler unit furthermore allowed limiting the ignition area on to left and middle area of the engine. This corresponded with the driver’s statement. A close examination of this area showed a broken line of the injection system. The analysis of the line of breakage showed clearly that the line was broken before the fire and that it was not caused by the fire.

After breaking diesel fuel was spilled in the engine compartment under high pressure. The turbo-charger and other parts of the exhaust system provided the energy to ignite the diesel. With the whole area being sprinkled with diesel the fire spread very fast. This is also the explanation for the dark smoke the driver had reported.

A further investigation of the line of breakage and the fitting parts showed tool marks at a coupling nut. The nut had been fixed with a too high torsion moment. As a consequence the vibrations while operation damaged the line, leading to the breakage. The documentation of the EvoBus garage contained no repair works requiring a loosening of that nut. Inspections and oil changes had been carried out by the operator’s garage. Reports documenting these works had not been written.
The time from the line breaking until ignition of the spilled diesel fuel is supposed to be very short. After ignition the fire spread very fast with large amounts of diesel sprinkled in the engine compartment. Thus it was not possible for the driver to notice the fire earlier. With the high fire load offered in an early stage of the fire and the high temperatures generated it was not possible for the driver to fight the fire with just one fire extinguisher.

![Image of the bus destroyed completely and damaged driver area.](image)

**Figure 22** Pictures of the bus destroyed completely and damaged driver area.

![Image of the damaged engine compartment and area of the ignition around the turbo-charger.](image)

**Figure 23** Damaged engine compartment and area of the ignition around the turbo-charger.

![Image of the broken injection line.](image)

**Figure 24** Broken injection line.

![Image of the close-up view of the coupling nut of the line of breakage and the tool marks on the coupling nut.](image)

**Figure 25** Close-up view of the coupling nut of the line of breakage and the tool marks on the coupling nut.
CONCLUSIONS

In all selected cases the buses were riding. Most fires were first discovered by the smell of smoke or the emission of smoke. One bus was equipped with an automatic fire detection system in the engine compartment. Unfortunately the fire started in a non-screened area of the engine compartment. All fires started in areas not directly visible by the driver.

The sooner a fire is detected the better the chances are to get it extinguished with the on board fire extinguisher – and even more important: the longer is the remaining period of time to reach a safe place and evacuate the bus.

Automatic fire detection systems, as mandatory by the new European directives, have a high potential to minimize the time of detection. But, as seen in example 3, the sensors must cover all critical areas as good as possible. Further research is required here, especially for the engine compartment. Standards are desirable.

In all cases the passengers were able to leave the buses without injuries. Nevertheless automatic fire suppression systems would have been very useful to minimise the damages. In example 1 a suppression system would not have had any effect. The further development of standards and test procedures makes sense. Insurance companies and operators should be informed more about the benefit potential of suppression systems. Legal regulations are difficult to establish.

The quality of maintenance and repair is an important part in fire protection. The tight and narrow packaging of the bus engine compartments makes such work difficult and fault-prone [11]. Regular inspections by the drivers and operators can help detecting scorch spots.

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Commercial Vehicle Fire, Cause and Origin Analysis
(Mechanical, Electrical and Forensic Methods)

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ABSTRACT
Safety issues related to vehicle fires have been a longtime problem. The occurrence of large scale fires involving commercial vehicles needs to be addressed to minimize personal injury, property loss and business interruption. The occurrence of fires can begin to be minimized with the full understanding of their cause and origin. Specifically, if you know the root cause(s) of the fire, various product redesigns, system upgrades and maintenance processes can be developed to aid in the prevention and/or detection of the on-board fire. A method combining mechanical engineering, fire science, basic vehicle mechanics and forensic methods has been developed to determine the cause of large commercial vehicle fires [1]. Once the potential hazards are identified, the individual hazards’ care and maintenance can be monitored. Additionally, cause and origin analysis can lead to design improvements. In this paper case studies will be utilized to show examples of root causes of fires involving commercial vehicles. However, the reader should keep in mind that this investigation method can be used for any vehicle/equipment fire analysis. Due to space limitations it is not possible to include the illustrations in this version. Please contact the author for a fully illustrated version.

Keywords: Fire, Cause, Origin, Bus, Motorcoach, Truck, Heavy Truck

INTRODUCTION
Fire prevention in commercial vehicles should be a primary concern for manufacturers, operators and maintainers. Component and system knowledge is the key to preventing vehicle fires. New government regulations, put in place and enforced, by the U.S.D.O.T. and the C.V.S.A. are attempts to get operators and maintainers to inspect and repair vehicles. This has had some positive effects but not enough to ensure vehicle safety. Economic stresses work against the enforcement of these new regulations. Therefore, it is up to the motor carrier to self-enforce inspections and repairs of at-risk vehicles. Unfortunately, lack of system/component knowledge, misunderstanding and lack of inspection oversight further contribute to commercial vehicle fires. One purpose of this paper, through individual case studies, is to show and explain the mechanical/electrical causes of fires. Armed with this knowledge, operators, maintainers, designers and manufacturers can mitigate or eliminate fires.

As simple as it appears, if the vehicle is in motion certain items are valid as possible causes. Likewise, if the vehicle is stationary with the engine on or off other items become potential causes. In either case, the situation is dangerous and costly in both human life and property.

DISCUSSION
Over the past 25 years the author has investigated numerous fires involving Motorcoaches, Heavy Transit buses, Heavy Trucks and Off-Road equipment. Several technical papers have been written by this author [1, 2, 3, 4] and will be used as reference within this paper to add detail both written and visually with case study photographs. The subject of fire investigation is broad, therefore, one purpose of this paper is to expose the reader to elements of investigation techniques and component functionality to rapidly educate them on the subject.
The most common causes discussed here are not ranked in order of likelihood. The operational profile and vehicle history can help determine which of these trouble spots need attention first. Items to be discussed in this paper are:

- alternator(s)
- starter
- batteries
- battery cables
- fuel/combustible materials/lubricants
- hubs/bearings
- brakes (drum & disc)
- tires
- turbochargers
- sensors
- auxiliary heaters (diesel furnace)
- auxiliary power units
- 2007 emission schemes (diesel particulate filters)
- chassis/vocation related components (trucks)

**WHAT IS REQUIRED FOR A FIRE**

Three elements are needed to create a fire: air, a combustible material and an ignition source. These three items form what is known as the Fire Triangle; if any one of the three elements of the triangle is not present a fire cannot occur despite the presence of the other two.

Air is all around us; making for an abundant supply of the first element. A combustible material, the second element, is any thing that may be present on the vehicle such as diesel fuel, power steering fluid, engine oil, transmission fluid, gear/hub oil, grease and tires to name a few. The third element, the ignition source, can come in many forms. An open flame, a sustained duration, high energy spark, and auto-ignition are the most common ignition sources. Along with the completion of the fire triangle, atomization of the liquid must occur in order to satisfy the stoichiometric requirements (14:1) to burn. Absent this proper air-to-fuel ratio, the substance is deemed too rich to burn and will not ignite.

The atomization increases the surface area of the liquid by creating small spheres or droplets. For example, by taking a cube of 16 cubic cm. (1 cubic in.) in volume and simply dividing it up into five equal spheres, each 1/5 of 16 cubic cm. (1 cubic in.), the total surface area of the five spheres is 37% more than the surface area of the original same volume of 16 cubic cm. (1 cubic in.).

This increase in surface area is what allows the air to properly mix with the liquid for the stoichiometric ratio to be satisfied. As an example, this atomization usually comes from a spraying of the liquid from a pressurized pinhole leak in a hose or component housing. Once this ratio has been met a fire can occur.

**TEMPERATURE MAPPING**

Temperature mapping is a technique used to determine the surface temperature of various components on the vehicle. By using a non-contact laser thermometer, a map of component surface temperatures can be established for any particular vehicle. For this study an MCI DL-3 motorcoach was used.

The purpose of such a study is to verify individual component temperatures to assist in the cause and origin analysis, as well as fire prevention. A sample of surface temperatures has been provided in Appendix A. As you can see from this, certain components are normally at the auto-ignition temperature of the on-board fluids and some are not. What can be taken from this is that if the “cooler” components are functioning normally, they cannot be an auto-ignition source. If a fire was to be traced back to a “cooler” component, such as a drive axle hub, that would indicate that this component experienced some type of mechanical failure which preceded the fire and became the triggering element – the ignition source. In summary these “cool” components cannot become an ignition source without experiencing a localized failure due to the fact that their normal operating (surface temperature) is less than the average (on board fluid) auto-ignition temperature.
DAMAGE PATTERN ANALYSIS
This analysis involves the observation of flame/heat damage patterns leading to the origin of the fire. The technique is generally comprised of the elements shown in the flow chart from N.F.P.A. 921. This method is further facilitated by reassembling the vehicle (as much as possible) to show configuration and component placement.

By following this basic process, investigators can begin to focus in on elements which may have led to the beginning of the fire. However, throughout this process a high level understanding of the components and systems functional behavior must be known to the investigator.

PROCESS OF ELIMINATION
In many fires, the origin evidence is burned. This leaves the investigator with a difficult task. A method of analysis, if left with this situation, is to systematically eliminate ignition and combustible sources one by one using observations, mechanical function, system logic and reconstruction. Each of the components listed in the common causes section of this paper should be evaluated. For example, the rough edges on a turbocharger connection indicate a traumatic impact failure. Therefore, these turbochargers were knocked off the engine in the accident phase, and were not involved in the fire.

IGNITION SOURCE
**Alternator:** Most motorcoaches use either a large oil cooled gear/belt driven alternator or a more conventional style alternator similar to an automotive application; but larger. The typical varieties are a Delco 50-DN or an air cooled dual Bosch T1 configuration. The author must stress that these manufacturers are not being singled out for any particular reason; however, they are the most commonly found units within this type of vehicle. For most applications, the charging system for the motorcoach produces 275 amperes or more – as much amperage as a typical single family home may have. With this, the alternator (and system) carries great potential as an ignition source.

Typically with a 50-DN installation, the B+ (direct battery feed) cable is routed to a large stud on the back of the alternator. This in turn is held in place with a nut (to the stud) along with various clamping methods to secure the cable end from any movement.

These connections must be quality checked after the alternator has been installed and inspected periodically as well as to ensure there is no movement. *It is noteworthy to point out that with some applications, these cables may need to be temporarily removed to facilitate other non-alternator related repairs. The same care and vigilance should be used whether alternator or other repairs are being made.* If the B+ cable is loose, it can, by its own weight either fail the plastic insulator material surrounding the stud at its base, internal to the alternator, or wear through the cable insulation locally and make unwanted contact with the support bracket. When this occurs the cable can act similarly to an arc welding machine and cut its way through the bracket.

Once the B+ cable end is free, the cable can drop, making contact with a ground source, resulting in a sustained duration, high energy spark. This is exceptionally critical in that with some engine applications the alternator is installed above and on the fuel side of the engine.

In addition to the cable and its mounting system there is another potential fire hazard. When installing the B+ cable to the stud (50-DN) the proper torque must be used to ensure that the plastic material (internal insulator) is not broken or compromised in any way. If this nut is over-torqued, or otherwise installed incorrectly, it could lead to a loose stud subsequently leading to an ignition source and fire.

For most truck applications, the charging system for the truck/tractor produces 160 amperes or more. With this, the alternator (and system) carries great potential as an ignition source. During normal operation the alternator is producing anywhere from 12-18 volts (12 volt system) and 24-32 volts (24 volt system). As stated earlier, this is accompanied by amperage rating from 160-300 amps. Positive (B+) and negative cable connection condition is vital for safe operation.
BATTERIES / CABLES / DISTRIBUTION / ELECTRICAL SYSTEM

These elements of the electrical system carry and distribute the electrical power throughout the vehicle. Battery location, cable routing and securement, along with control elements, all have the potential to become ignition sources.

Battery location is an important design element within any vehicle. The placement of the batteries, in some cases, can be impacted in the collision phase of an accident. This can lead to becoming an ignition source of a fire. This is explained in greater detail in Reference 3.

TRUCK/TRACTOR SIDE IMPACT

In the event of this type of collision, most cars’ front bumper will contact the fuel tank of a truck tractor on or about the tank’s longitudinal center line. The same goes for pickup truck, S.U.V.’s and other trucks/tractors’ front bumpers. This event may then lead to a fuel spill. Additionally, the placement of the battery box in such close proximity to the fuel tank can become an ignition source for the potentially spilled and/or atomized (spray) diesel fuel.

Automotive bumpers range in height from approximately 33 – 58 cm. (13 – 23 in.) from the ground:

- Tractor fuel tank centerline approximately 61 cm. (24 in.) from ground
- Tractor battery tray/bracket distance to fuel tank approximately 5 cm. (2 in.)
- Tractor battery tray approximately 64 cm. (25 in.) from ground

A study of various truck tractor battery box and fuel tank locations was conducted. As stated earlier, the contention is that in most cases the battery box resides within centimeters (inches) from the fuel tank. This package of components is not unique to any one manufacturer.

In some cases the battery box can be as close to 6.4 cm. (2.5 in.) from the fuel tank. One possible solution to this hazard is moving the batteries in between the two chassis frame rails.

Freightliner Corporation has employed a design scheme since 1996 which, in most cases, precludes this hazard. On many of their tractors Freightliner installs the batteries inside the frame rails. The battery cables are nested inside the frame rails along with the batteries. This design, assuming this area is not intruded upon, provides protection from impact in most cases. The fact that the battery is now no longer adjacent to the fuel supply, significantly reduces the fire hazard. In other words, it takes the potential ignition source out of play from the fuel source, thus reducing the risk of the fire/explosion hazard. This design scheme has been installed on tractors with a wheel base as short as 411 cm. (162 in.), as well as long wheelbase sleeper tractors. As a result, packaging typically is not a design constraint.

Cable routing and securement is usually a packaging and “house-keeping” item with respect to vehicle design. Cable routing and securement goes hand-in-hand. Loose, pinched, excessive length or breached B+ cables(s) can lead to a high energy sustained duration spark which can become an ignition source. For example, a forensic signature known as “balling”, a term used to describe the physical appearance of a cable which has experienced a separation under power, can be seen locally at the point B+ to ground contact has been made.

Cables which can be contacted during the collision phase of an accident can become an ignition source. The securement of the cable(s), once routing is established, is vital to prevent the breaching of the insulation or the mechanical failure of a cable connector. In some cases, over time, a B+ cable can move cyclically enough that it will eventually make contact with chassis ground creating a sustained duration, high energy spark. In this case a simple clamp (p-clamp) was omitted during assembly which allowed the B+ cable to dangle enough so it contacted a structural gusset creating arcing.
FIRES WITH ENGINE OFF
As discussed earlier, fires can start with the engine off and after an extended period since the shut-down. When these facts are present, the investigator should focus on ignition sources that are (B+) with the ignition in the off position. Specifically, items which are (B+) energized all the time, regardless of ignition position. These are, but not limited to:

- Battery cables
- Batteries
- Brake booster motors
- Alternator
- Starter
- Master power distribution to cab
- Anything wired (B+)

Items which are energized by the vehicles ignition circuit are (normally) not an ignition source with the ignition in the off position. Therefore, they can generally be eliminated during the analysis.

In some instances a fire has begun with the vehicles’ engine off and after some period of time since the most recent engine shut-down. This can be attributed to an internal alternator failure; is some instances a diode failure. Diodes act as a one-way check valve for current. Typically, if a diode fails in this scenario, positive (B+) battery voltage/current goes to ground and has been known to start a fire.

AUXILIARY POWER UNITS (A.P.U.)
Some heavy trucks and custom motorcoaches utilize an auxiliary power unit (A.P.U.) to provide air conditioning, heat or electrical power while the engine is off. These need to be inspected and analyzed to determine if they are related to the fire. The A.P.U. is similar to the vehicle engine in that it has its own starter, alternator, fuel system, lubrication and electrical distribution system. Each of these items needs to be analyzed to determine if any were related to the fire. Additionally, the A.P.U. can also be an auto-ignition concern and must be evaluated in that regard.

Remote Jump Post: With some truck/bus applications a convenience feature is provided in the engine compartment for “jumping” a disabled vehicle. This is typically a positive (B+) cable running from the starter to an exposed stud. These connections must be inspected and maintained to provide integrity. Additionally, this stud should be covered with a flexible rubber boot.

This boot must be in good condition and over the positive (B+) stud at all times. A loose jumping stud/cable can create a sustained duration, high energy spark similar to the alternator B+ cable.

Starter: Most heavy vehicles use either a Delco 42MT or 50MT starter. Under normal circumstances the starter draws 800 to 1000 amps respectively while cranking the engine. When it is not cranking the engine (no current flow) it is simply exposed to battery voltage. As with the alternator, the starter is connected to the batteries via a B+ (direct battery feed) cable. It too is routed to a stud on the starter motor. However, this is initially routed to a bulkhead junction (motorcoach); again this is a heavy cable and must be properly connected and supported in its mounting. Another area of concern is the bulkhead pass-through for the battery (B+) cable to the bulkhead junction and engine compartment. Maintainers need to ensure that the (B+) cable is protected as it passes through this point. Care must be given to the cable condition, cable to starter connections, as well as its’ routing so that this B+ cable is not making unwanted contact and potentially coming in contact with ground as a result of an insulation breach. The starter should be treated and cared for in the same manner as the alternator since it resides on the fuel side of the engine in some applications.

COMBUSTIBLE MATERIALS
In some cases, the onboard fuel supply can be a causal element in a fire. In order for the fuel to ignite, the surface temperature of the engine and related components must be at least at the auto-ignition temperature of diesel fuel. All of the liquids; fuel, power steering fluid, engine oil and hub/gear oil, found on the vehicle have an auto-ignition temperature. If one or more of these fluids were to come in
contact with a sufficiently hot surface at auto-ignition temperature; that fluid would ignite in the absence of an open flame. To minimize fluid fires, all hoses, housings, couplings, fittings and filters must be inspected diligently to reduce or eliminate leaks which could lead to a fire. Practically speaking, the first step is to regularly clean the engine, transmission and interior surfaces of the engine compartment. This has a triple advantage to the operator. First, oil and road dirt covering the engine will act to insulate it holding in engine heat. Second, when the engine is clean it is easier to locate a fluid leak. Lastly, with a clean engine, you reduce the risk of fire and it spreading by virtue of not having any combustible materials on the engine itself. Investigators should observe flame/heat patterns in the engine compartment/room as a further cause and origin method.

**HUB FAILURE**

Wheel hubs low on oil can have an elevated operating temperature high enough to ignite the surrounding combustible materials by auto-ignition. Coincident to this, in some cases, is a wheel end failure resulting in a “wheel-off” situation. Typically, the outer wheel bearings’ lowest point is above the lowest point of the hub seal. Therefore, since the outer bearing is at that elevation, it starves for oil first. The inner bearing is at a lower point in the hub and is usually bathed in oil for a longer period of time. There are two common failure modes for the hub (non-driving) to be low on oil: hubcap failure and seal failure. The hubcap can have at least four failure modes: the plastic site glass, o-ring, the rubber plug and the mounting gasket. For any of these reasons the hub can become low on oil. As for a drive hub, the axle flange gasket or seal can be a leak point allowing the hub to become low on oil. It is noteworthy to mention that when the seal wiper becomes worn (grooved) it may create a leak point despite the integrity of the seal itself. The wiper should be inspected each time the hub is removed and changed if it appears to be excessively worn. In some cases, during a wheel bearing failure, the vehicle’s A.B.S. dash light may become illuminated as a result of the sensor-to-hub gap becoming greater due to the hub beginning to come off of the spindle or axle tube or from a skidding or locked tire/wheel.

The A.B.S. control module can, in some cases, be downloaded after the incident in order to determine whether or not the A.B.S. system detected a failure prior to the fire – such as a skidding tire due to a bearing failure. This information can be assistive in the cause and origin determination.

One case study showed that the cause of a trailer fire was due to a hub failure. This failure was caused by low hub oil level. This condition ultimately led to the fire which started at the tire. This is indicated by the deformed (melted) bearing rollers. Bearing rollers, with this appearance, can only occur when the hub oil level is low. This deformation can not occur due to the fire. Low hub oil levels create extremely high heat. The weight of the load, that the bearing supports, creates pressure on each bearing roller. This pressure coupled with the extreme heat creates the rollers deformation. Once this occurs, the tire(s) near this area can ignite.

An additional risk exists, with disc brake applications, during a wheel bearing/hub failure. That is, as the outer bearing begins to fail, the hub load is transferred from the outer bearing to the brake caliper, brake pads and rotor. Once the outer bearing has failed completely, no longer able to support the hub load, the caliper, brake pads and rotor are then supporting that particular wheel end.

This is due to the fact that the caliper rides in the caliper carrier which is attached to the spider (torque plate) which is mounted to the axle tube/spindle.

Once the brake caliper begins carrying the load, at that particular wheel end, the surface temperature of the brake pads and rotor (or drum) rise well above the auto-ignition temperature of the surrounding combustibles (due to friction) and eventually igniting them. The combustible material typically ignited by this failure mode is the tire(s). Tires generally revert (melt) at approximately 121°C (250°F) and catch fire over the 316°C (600°F) mark. It is common, although not mandatory, for the tire fire to occur when the vehicle comes to a stop. This is the condition with the least amount of air
flow circulating around the brake rotors, brake drums and tires. Without air flow around these items, their temperature rises rapidly and is transmitted to the tire—subsequently igniting it. This concept of brake caliper/pad/rotor supporting the hub load can typically be seen by observing non-parallel brake pad contact surfaces. This is due to the hub moving outward, away from the spindle. As a result of this temporary load support from the caliper, the operator may continue to drive the vehicle without any indication of a problem until it is too late.

**BRAKES**

*Disc Brakes:* A “frozen” disc brake caliper can generate enough heat to ignite the surrounding combustible materials and sustain a fire. Proper inspection and lubrication intervals should be adhered to along with a periodic activation and release sequence confirming that the calipers are releasing and allowing the rotor to turn freely. This scenario applies to both air and hydraulic disc brakes. A simple method to determine the proper action of the calipers is to insert a feeler gauge (.005 - .010 cm.) (.002 - .004 in.) between the brake pad and rotor. By applying the service brakes a technician can feel if the gauge goes into this space, remains there upon brake application and is then released upon release of the service brakes. In some early applications, Rockwell disc brakes were used which in some instances were not supplied with grease fittings in the calipers. This very point leads to a “frozen” caliper scenario which, in the author’s direct experience, results in a fire at that wheel end.

*Drum Brakes:* Drum brakes can create a fire hazard similar to disc brakes by supporting the hub load, during a bearing failure or by a partial application (stuck) brake. Specifically, if the brakes are applied during vehicle motion, through either the service or parking system, they can create enough friction, leading to extreme heat, that they can cause a tire fire or ignite some other combustible material. Over the last 20 years, engine manufacturers have continually produced engines with high horsepower and torque ratings. These high output engines are capable of driving through a partially applied service brake or fully applied parking brake. If this was to occur at highway speeds, enough frictional heat can be developed to start a fire.

Various pneumatic and mechanical issues can prompt a brake failure which can lead to a fire. Generally speaking, when drum brakes approach this scenario, they leave signatures. Brake drums may show signs of rouging and the matching brake blocks may show a burn pattern if not damaged by the fire. In the extreme case the brake blocks can become fused to the drum as a result of the bonding agent (resin) of the brake blocks actually beginning to melt and burn.

In some cases, the service brake (pedal) can become “stuck”. Specifically, it can fail to come back to the non-applied position. This is (usually) caused by corrosion and or debris buildup which is collected at the base of the pedal’s pivot pin. Unknown to the driver, he/she could be operating the vehicle with the service brakes partially applied. This creates heat buildup in the brake system. This can eventually lead to brake and wheel end (bearing) overheat. One tell-tale sign of this condition is the continuous illumination of the “stop light” dash light. Additionally, if the vehicle has aluminum wheels, some are supplied with a temperature sensitive sticker affixed directly to the wheel. If this sticker has turned a dark brown color, the wheel has experienced an abnormally high heat load. This requires further diagnosis into the brake and wheel end components.

**TIRES**

A flat or under-inflated dual tire can become a fire hazard and in some cases go undetected. Dual tires are spaced apart to provide a gap.

If the adjacent tire is under-inflated the gap closes and the tires begin to “kiss”. Since an under-inflated tire only bulges at the road surface, a cyclical contact event occurs between the inflated tire and the under-inflated tire. Over time this cyclical contact may generate heat increasing the tires temperature. Therefore, operators should always ensure that all tires, especially dual tires, are inflated and not in contact with one another. In general, operating temperatures for radial tires can be
anywhere between ambient plus 16°C (60°F) (66°-82°C) (150°-180°F). Under severe conditions the operating temperatures will range in the 93°C (200°F) areas.

Tires which have ignited during (rotation) travel can be indicated by the disturbance or twisting of the tire reinforcing cords. Tires that have ignited while stationary (no rotation), have tire cords which remain largely undisturbed. In general, tires do not become a fire hazard on their own. In most cases it takes a localized failure of an adjacent component to ignite the tire(s).

**TURBOCHARGER**

Turbochargers are a dual threat as an ignition component. First, since they are typically very hot, on the surface, they can act as an auto-ignition source. Second, upon their own internal failure, they can become an ignition source by virtue of their own internal lubrication oil. The typical turbocharger supports the shaft of the compressor and turbine with a non-conventional bearing. This is unlike the typical roller bearing. Instead the shaft is supported by two bearing collars which are supported by the boundary lubrication layer.

Upon a failure of this bearing system or an imbalance of either the turbine or compressor wheels contact is made within the turbocharger housing causing a rapid deterioration of the compressor and turbine.

Once the shaft has been re-oriented as a result of any one of the aforementioned failure modes, the shaft seal(s), which controls the lubrication oil within the bearing cavity, subsequently fails allowing oil to enter directly into the hot side (turbine) of the housing and then directly into the exhaust system. This can create and auto-ignition fire within the turbocharger itself or exhaust system. Some engine manufacturers have reprogrammed engine management software to detect the symptom of this failure. The engine’s Electronic Control Module (E.C.M.) monitors turbocharger boost pressure for performance and engine management control purposes. With the change in software, the E.C.M. now sets a fault code for low boost pressure which could indicate an internally failed turbocharger.

However, if the engine in question precedes any recent software change, two other simple methods can be used to detect the onset of an internal turbocharger failure. If the turbocharger has experienced an internal failure the performance of the engine is compromised. Specifically, blue smoke, due to oil consumption along with reduced engine torque will be noticed. Also a specific oil leak, from the waste gate pivot point, can be observed. Once oil has begun to leak from this point on the turbocharger it should be removed from service and the exhaust system should be thoroughly cleaned. To assist in preventing this failure mode; the turbocharger waste gate or variable geometry function (V.G.T.) must be confirmed. Additionally, the shaft free play, both axially and radially, must be inspected by a mechanic.

These two systems regulate turbocharger boost pressure. If they were to fail to regulate this pressure, it may lead to an internal failure, as a result of over pressurization and/or over-speed, thus leading to a fire. Additionally, the shaft free play, both axially and radially, must be inspected by a mechanic.

To confirm the function of the waste gate, apply regulated air pressure to the boost line (1.4-2.1 bar) (20-30 psi) to exercise the waste gate slave cylinder. To confirm the V.G.T. function, turn on the vehicles’ ignition to “on” and observe the slave cylinder motion.

If there is no motion for either system upon these diagnostic tests, they are defective and must be replaced/repaired. These two systems regulate turbocharger boost pressure. If they were to fail to regulate this pressure, it may lead to an internal failure thus leading to a fire.

*External Turbocharger Oil Lines:* With the Detroit Diesel Series 92 application, there is only one external oil line. The oil supply line is positioned on top of the turbocharger and must be inspected periodically for leaks.
With most 4-stroke inline engine applications, the turbocharger has two oil lines which need to be periodically inspected. These turbochargers have an external supply and return oil line. In either case, a leaking oil line must be repaired to prevent an auto-ignition fire.

**SENSORS**
In most applications there are sensors which are exposed to either fuel, engine oil, transmission fluid and hydraulic oil, to name a few. These sensors are typically diaphragm type; that is to say, an internal diaphragm is moved by the fluid pressure inside the sensor/switch. Since pressurized fluid enters these sensors/switches it is vital that they be periodically inspected for leaks. Based on their position on the engine/transmission they may become a source for a combustible material which may come in contact with an ignition source and initiate a fire.

**AUXILIARY HEATERS**
Also known as diesel furnaces, auxiliary heaters heat the onboard coolant when the engine is not running or to assist with emissions. However since it is a furnace which burns diesel as fuel it must be periodically inspected for function, control and integrity. Specifically, its cycle time and control must be verified to assure it is functioning when it should be, as well as, turning off when commanded. Additionally, the fuel lines must be inspected to confirm there are no leaks. In fact, in the summer months it is good practice to disconnect the heater function power supply and loop the supply and return fuel lines together. This will assure that fuel does not leak from the furnace itself when not in service. It should be pointed out that the heaters’ exhaust pipe, within minutes of heater activation, reaches 191°C (375°F) and continues to climb approaching the auto-ignition temperature of most of the vehicles fluids. Therefore, it is vital that any leak, of any fluid in this area, be immediately repaired to minimize high temperature contact and subsequent fire.

In some cases, a motorcoach with an auxiliary heater is parked in an area with combustible materials. In one specific case, the motorcoach was parked with the rear of the vehicle over grass and dry leaves. Since the auxiliary heater exhaust pipe resides under the rear bumper, the hot exhaust washed over the grass and leaves igniting them and burning the bus. Therefore, operators need to be careful where the vehicle is placed during auxiliary heater run-time.

**2007 EMISSIONS SCHEMES**
At the time of this publication a large number of engines with regeneration capability are in the stream of commerce. The design suggests regenerating (cleaning) the particulate trap by elevating its temperature to burn off the material trapped inside°. The regeneration process converts ash and soot, which is trapped in the diesel particulate filter (DPF) and converts it to carbon dioxide. In order to do this the engine must create exhaust gases with high enough temperatures to complete this process. In some designs, during regeneration, raw fuel is injected near the turbocharger, via a doser, increasing the temperature of the exhaust gases to 649°-816°C (1200°-1500°F). As with any other component, with a high (>221°C) (430°F) surface temperature, leaks in the immediate area must be repaired to avoid contact with this system while it is regenerating the DPF. Lastly, this systems’ interlocks, which dictate when it can function, must be confirmed to be working to avoid a cycle of regeneration at a time or location which is undesirable.

**ADDITIONAL IGNITION SOURCES**
Additional body related ignition sources are:

- Evaporator motor(s)
- condenser motor(s)
- defroster motor(s)
- A/C compressor clutch coil/wires
- Radio
- G.P.S. systems
- Dash board wiring
- Air dryer heater wire
- Headlight wiring
- Air conditioning, high/low pressure switch wiring; typically carries a ground signal. This can usually be ruled out as an ignition source.
• A.B.S. Signal wiring; typically carries an inductive low voltage (mili-volts) signal to the A.B.S. controller. This can usually be ruled out as an ignition source.

• Engine Starting Aids (Starting Fluid Canisters)

These systems must be inspected periodically for proper wire/cable routing and support along with proper (B+) connections and wire insulation. Usually not a leading fire cause they must be as vigilantly inspected as any other component on the vehicle.

CHASSIS COMPONENTS
Some trucks with hydraulic brakes, utilize an emergency brake booster which is powered by an electrical motor. This system is intended to provide boost assistance to the brakes during an engine stall. Without this system, the operator would not be able to provide enough force, by his/her foot, to stop the vehicle. This system is wired to battery power (B+). That is to say, it is powered all the time regardless of the position of the ignition switch. Consequently, this can become an ignition source even when the engine is off and has been parked for some time.

VOCATIONAL COMPONENTS
Vocational components and systems are utilized to perform the intended task of the vehicle. For example, a fuel truck may need to pump fuel, from its tank, to the intended storage tank of the customer. Numerous failure modes of the overall system can create either an ignition source or provide the release of the combustible materials. This is further explained in Reference 2.

DIESEL ENGINE RUNAWAY
When a diesel engine is exposed to an external fuel source such as an airborne combustible hydrocarbon in the surrounding environment, it naturally ingests the mixture into the air intake system. Since diesel engines control fuel and not air, the engine can no longer maintain speed control. Once this occurs the engine can create a destructive “back fire” which can ignite the surrounding environments.

If the engine has ingested enough external combustibles and runaway, the probability of fire dramatically increases. As the engine instability increases in magnitude, the likelihood of a “destructive backfire” increases. Specifically, the intake ducting and manifold fill with combustibles and due to valve float, the combustion process is now open to the intake system, igniting the volatile mixture and creating a fire that moves backwards through the intake.

The destructive backfire is evidenced by a damaged turbocharger outlet elbow or other air intake system parts. Typically, the part is broken off of the turbocharger and “blown” clear of the main fire area. Damage to the 90° elbow and rubber hose is indicative of an explosion, not fire damage or heat.

THE SOLUTION
With all varieties of diesel engines, the common denominator is combustion air. Diesels have a multitude of fuel control schemes but utilize air the same way. Therefore controlling combustion air is the key to absolute engine control during an emergency.

The first and most direct method for eliminating a runaway is to simply shut off the engine at the loading/unloading destination. If there is a need to keep the engine running, an air intake shut-off valve can be installed. These valves come in two varieties: passive and active. The passive system is automatic and sensitive to engine RPM. If the engine exceeds a preset RPM it will shut off the engine by eliminating combustion air. Active systems are usually controlled by the driver by a pull cable or a push button. When activated, a gate swings shut and positively blocks the combustion air path between the air cleaner and the turbocharger resulting in total shut down of the engine.
CONCLUDING REMARKS
The purpose of this paper is to bring to the attention of manufacturers, owners, operators and mechanics that methods are available which can mitigate this type of accident. A general inspection list has been provided (see Appendix C) to further assist the reader in preventing vehicle fires. This list of items can be included in a Preventative, Periodic and Annual Maintenance Inspection Program. Additionally, some of the inspection items may be incorporated into a daily driver (pre/post trip) inspection. Furthermore, it is to assist the investigator in conducting fire cause and origin analysis of vehicles involved in this type of occurrence as well as to show the mechanical finger prints which are associated with it.

REFERENCES
1). Ferrone, C.W., “Fire, Cause and Original of Heavy Vehicles (Mechanical and Forensic Methods),” American Society of Mechanical Engineers paper #IMECE 2009-10522.
3). Ferrone, C.W., “Fire and Explosion Investigations; Why Heavy Trucks May Burn,” American Society of Mechanical Engineers paper #IMECE 2006-13305
7). Bridgestone Commercial Tires (Tire, M.D.)
8). Detroit Diesel Corporation; S-60 Burst Logic Safety Recall, NHTSA-06E-019, DDC: 06C-4.
APPENDIX A

Surface Temperatures in °F/°C

Ambient Temperature (85°F / 29°C)

- Disc Brake Rotor - 420° / 215° MCI DL-3
- Drive Axle Hub - 150° / 65° MCI DL-3
- Steering Axle Hub - 137° / 58° MCI DL-3
- Tag Axle Hub - 166° / 74° MCI DL-3
- Turbocharger [hot] - 607° / 319° DDC S-60
- Turbocharger [cold] - 198° / 92° DDC S-60
- Exhaust Manifold - 390° / 198° DDC S-60
- Exhaust at Turbocharger Inlet – 585° / 307° DDC S-60
- EGR - 261° / 127° DDC S-60
- Engine Block [side] - 232° / 111° DDC S-60
- Transmission Housing - 198° / 92° Allison B-500

Note: These are examples only and are not meant to represent all temperatures found on a motorcoach, transit or school bus.

APPENDIX B

Auto-Ignition Temperatures in °F/°C

On Board Fluids

- Diesel Fuel - 446° / 230°
- Power Steering - 417° / 213°
- Engine Oil - 449° / 231°
- Transmission Fluid - 417° / 213°
- Coolant (50/50) - 903° / 483°
- Hub/Gear Oil - 428° / 220°
- Tires (smoldering) - 450-500° / 232°-260°

Note: These are examples only and are not meant to represent all types and varieties of fluids found on a motorcoach, transit or school bus.

APPENDIX C

Preventative, Periodic, Annual and Daily (Pre/Post Trip) Maintenance and Inspection Items

- B+ Cable at alternator secure (stud, bracket and clamps in position)
- Alternator oil lines and rear cover plate secure and not leaking
- All alternator electrical studs covered with rubber boots
- Remote Jump Post secure and stud covered with rubber boot
- Starter cables secure and routed properly
- Bulkhead connection for B+ cables (starter and alternator) secure
- Engine compartment clean/dry of fluids
- Engine and Transmission fluid connections/hoses secure and not leaking; sensors not leaking
- No leaks dripping onto pavement
- Hub-Caps; no visible leaks, rubber plug in place, sight glass is clear, oil at proper level
- Oil seals are in good condition, no leaks (only observable from under vehicle)
- Disc brake rotors (if visible) clean with no bluing
- Dual tires not making contact with each other
- Turbocharger oil line(s) not leaking, waste gate pivot pin not leaking oil
- Exhaust system; no oil exiting from muffler, no excessive blue smoke (turbocharger oil consumption)
- Engine has appropriate performance (torque)
- Auxiliary heater not leaking fuel
- No active / Illuminated A.B.S. dash light (The illumination of this light could indicate the potential onset of a loose wheel bearing, hub run-out, wheel bearing failure or a skidding or locked tire/wheel.)
Automobile Fires in the U.S.: 2006-2010 Estimates

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Quincy, MA, USA

ABSTRACT

Automobile fires account for the majority of vehicle fires and vehicle fire deaths. It is necessary to address automobile fires if major reductions are to be seen in the overall vehicle fire problem. Any efforts to evaluate the merits of proposed fire safety improvements require an understanding of how many fires and deaths are presently occurring and how many might be prevented with the proposed improvements. In this paper, data from the U.S. Fire Administration’s National Fire Incident Reporting System (NFIRS) and the National Fire Protection Association’s (NFPA’s) fire department survey were used to estimate the frequency and associated losses of automobile fires attended by local U.S. fire departments, and the major factors in these fires and losses. The risk of automobile fires, associated deaths overall and from fires resulting from collision or overturn per billion kilometers driven are also included. The majority of automobile fires resulted from mechanical or electrical problems, but three out of every five automobile fire deaths resulted from fires started by collision or overturn.

KEYWORDS: automobile fires, fire statistics, fire risk

INTRODUCTION

During 2006-2010, U.S. fire departments responded to an average of 152,300 automobile fires per year, resulting in annual averages of 209 civilian deaths, 764 civilian injuries, and $536 million (US) in direct property damage. Table 1 shows that automobiles accounted for two-thirds (68%) of reported road vehicle fires and 63% of the associated deaths. In addition to automobiles, road vehicle fires include other types of passenger road vehicles, such as buses, recreational vehicles and motorcycles, and freight road transport vehicles, such as trucks.

Overall, automobile fires accounted for 10% of all reported U.S. fires (excluding those handled by private, state or federal firefighting agencies) and 6% of the associated fire deaths. During this period, there were 1.4 fire deaths per 1,000 reported automobile fires. With almost 131 million automobiles registered in the U.S. during 2010 [1], these vehicles are essential to getting people where they need to go. In most years, more people are killed by automobile fires than by non-residential structure fires. [2] While progress has been made, there is more to do. It is necessary to understand the causes and circumstances of these fires in order to develop sound strategies to prevent these fires and losses. These factors, as well as fire and loss rates based on distance travelled, fire department response times, and automobile fire and fire death trends are discussed. Data issues and limitations are also addressed.

METHODOLOGY

This paper focuses on automobile fires reported to local (municipal or county) fire departments in the U.S. National estimates of fires and associated losses were calculated using the detailed data and data classification system from the U.S. Fire Administration’s National Fire Incident Reporting System (NFIRS) [3] and the National Fire Protection Association’s (NFPA’s) fire department experience survey following the general procedures described by Hall and Harwood. [4] Fire departments throughout the U.S. use NFIRS to document their incidents. Generally, state fire authorities
administer the NFIRS program for their state, providing training, support and quality control. States set their own reporting requirements, ranging from mandatory for all incidents, to mandatory for incidents meeting a loss threshold to completely voluntary. Participation in NFIRS is voluntary at the federal level. Note that fires that are reported to federal, state or private firefighting organizations are not captured in NFIRS. Fires that are handled without fire department assistance are also not captured.

Table 1. Road vehicle fires reported in the U.S., by vehicle type: 2006-2010 annual averages

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Fires</th>
<th>Civilian Deaths</th>
<th>Civilian Injuries</th>
<th>Direct Property Damage (in Millions US)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passenger road vehicles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automobile, passenger car, ambulance, race car or taxi-cab</td>
<td>202,800 (91%)</td>
<td>277 (84%)</td>
<td>1,077 (88%)</td>
<td>$776 (76%)</td>
</tr>
<tr>
<td>Unclassified passenger road vehicle</td>
<td>152,300 (68%)</td>
<td>209 (63%)</td>
<td>764 (63%)</td>
<td>$536 (52%)</td>
</tr>
<tr>
<td>Motor home, camper mounted on pickup</td>
<td>41,200 (18%)</td>
<td>56 (17%)</td>
<td>173 (14%)</td>
<td>$144 (14%)</td>
</tr>
<tr>
<td>Bus, school bus or trackless trolley</td>
<td>2,700 (1%)</td>
<td>5 (2%)</td>
<td>60 (5%)</td>
<td>$45 (4%)</td>
</tr>
<tr>
<td>Motorcycle or trail bike</td>
<td>2,100 (1%)</td>
<td>0 (0%)</td>
<td>22 (2%)</td>
<td>$29 (3%)</td>
</tr>
<tr>
<td>Off-road recreational vehicle</td>
<td>1,600 (1%)</td>
<td>3 (1%)</td>
<td>19 (2%)</td>
<td>$5 (0%)</td>
</tr>
<tr>
<td>Towable travel trailer</td>
<td>1,300 (1%)</td>
<td>3 (1%)</td>
<td>23 (2%)</td>
<td>$11 (1%)</td>
</tr>
<tr>
<td>Collapsible camper trailer</td>
<td>200 (0%)</td>
<td>0 (0%)</td>
<td>4 (0%)</td>
<td>$1 (0%)</td>
</tr>
<tr>
<td>Portable building or manufactured home</td>
<td>200 (0%)</td>
<td>0 (0%)</td>
<td>2 (0%)</td>
<td>$2 (0%)</td>
</tr>
<tr>
<td><strong>Freight road vehicles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-trailer, with or without tractor</td>
<td>5,900 (3%)</td>
<td>23 (7%)</td>
<td>38 (3%)</td>
<td>$92 (9%)</td>
</tr>
<tr>
<td>General use truck</td>
<td>4,600 (2%)</td>
<td>7 (2%)</td>
<td>32 (3%)</td>
<td>$39 (4%)</td>
</tr>
<tr>
<td>Unclassified freight road vehicle</td>
<td>4,600 (2%)</td>
<td>10 (3%)</td>
<td>30 (2%)</td>
<td>$68 (7%)</td>
</tr>
<tr>
<td>Pickup truck or hauling rig</td>
<td>3,000 (1%)</td>
<td>6 (2%)</td>
<td>23 (2%)</td>
<td>$14 (1%)</td>
</tr>
<tr>
<td>Garbage, waste or refuse truck</td>
<td>1,700 (1%)</td>
<td>0 (0%)</td>
<td>9 (1%)</td>
<td>$18 (2%)</td>
</tr>
<tr>
<td>Tank truck for flammable or combustible liquid</td>
<td>400 (0%)</td>
<td>4 (1%)</td>
<td>10 (1%)</td>
<td>$13 (1%)</td>
</tr>
<tr>
<td>Tank truck for nonflammable cargo</td>
<td>300 (0%)</td>
<td>2 (1%)</td>
<td>1 (0%)</td>
<td>$4 (0%)</td>
</tr>
<tr>
<td>Tank truck for compressed or LP-gas</td>
<td>100 (0%)</td>
<td>0 (0%)</td>
<td>1 (0%)</td>
<td>$1 (0%)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>223,300 (100%)</td>
<td>329 (100%)</td>
<td>1,221 (100%)</td>
<td>$1,025 (100%)</td>
</tr>
</tbody>
</table>

NFPA’s survey solicits summary data about major categories of fires and other incidents from all local U.S. fire departments protecting populations of at least 50,000 and a random sample, stratified by population, of smaller departments. Because a statistical sample is used, it is possible to estimate the total number of reported fires and losses. Estimated total vehicle fires and losses from each year’s NFPA survey are divided by the total vehicle fires and losses in NFIRS to create scaling ratios. NFIRS query results are multiplied by these scaling results to estimate the frequency of specific factors associated with vehicle fires or losses. The same approach is used with residential and non-residential structure fires, and outside or unclassified fires. Separate ratios are calculated for fires, civilian deaths, civilian injuries, and direct property damage.

Query criteria
In this analysis, automobile fires were identified by using the entire range of NFIRS vehicle fire incident types (130-139) and mobile property type 11 - automobile, passenger car, ambulance, race car or taxi-cab. Unclassified passenger road vehicles and pick-up trucks or hauling rigs were
excluded. Only data originally collected in Version 5.0 of NFIRS were analyzed. Fires in which mutual aid was given were excluded. Vehicle fires inside structures that involved the structure are considered structure fires and not included here. Only casualties caused by the fire are considered fire casualties. Trauma-only casualties should, by NFIRS and NFPA definition, be excluded. Over the five-year period of 2006-2010, raw NFIRS data contained a total of 446,926 automobile fires that meet these criteria, with 884 civilian deaths, 1,754 civilian injuries, and $1,371,288,438 in direct property damage.

Handling unknown or missing data in NFIRS
For NFIRS fields other than incident type and property use, unknown or missing data were allocated proportionally. A proportional share of vehicle fires in which the mobile property involved in ignition as coded as none were treated as unknown and included in the estimates. “None” was also treated as unknown in the factor contributing to ignition field.

Distance data
Data from the U.S. National Highway Traffic Safety Administration (NHTSA) were used to calculate event rates based on kilometers driven. [5] Because the data on kilometers (converted from miles) driven in 2009 were not shown separately for automobiles, annual averages for 2006-2008 were used in calculations involving distance travelled. Risk relative to exposure is useful for setting priorities and tracking progress.

CAUSES AND CIRCUMSTANCES OF AUTOMOBILE FIRES

A number of factors influence the outcome of a fire. The location of the fire can affect the likelihood of prompt discovery, fire department notification and timely fire department response. Some types of fires have a higher risk of death than others. The area of the vehicle where the fire originates also matters.

Where do automobile fires occur?
Roughly three-quarters (71%) of automobile fires and associated deaths (76%) occurred on highways, streets or parking areas. While only 17% of the fires occurred on highways or divided highways, Figure 1 shows that these fires caused 41% of the associated deaths.

Figure 1. Automobile fires, by leading location where fire occurred: 2006-2010

Table 2 and Figure 2 show the major causes of automobile fires. These causes were pulled from three NFIRS fields: cause of ignition, factors contributing to ignition, and heat source. The major casual factors describe specific scenarios. Because the field for factor contributing to ignition allows multiple entries and calculations were done separately for each field, double-counting is possible.
What are the leading causes of automobile fires?
Some type of a mechanical failure or malfunction was a factor on almost half (45%) of automobile fires and 11% of the associated deaths. Mechanical failures may be due to leaks or breaks, worn out parts, backfires, or similar issues. Electrical failures or malfunctions were factors in one-quarter (24%) of the fires, but only 1% of the deaths.

<table>
<thead>
<tr>
<th>Causal Factor</th>
<th>Fires</th>
<th>Civilian Deaths</th>
<th>Civilian Injuries</th>
<th>Direct Property Damage (in Millions US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical failure or malfunction</td>
<td>69,100</td>
<td>22 (11%)</td>
<td>217 (28%)</td>
<td>$201 (38%)</td>
</tr>
<tr>
<td>Electrical failure or malfunction</td>
<td>35,800</td>
<td>2 (1%)</td>
<td>113 (15%)</td>
<td>$105 (20%)</td>
</tr>
<tr>
<td>Intentional</td>
<td>15,900</td>
<td>23 (11%)</td>
<td>44 (6%)</td>
<td>$112 (21%)</td>
</tr>
<tr>
<td>Exposure fire</td>
<td>8,200</td>
<td>3 (1%)</td>
<td>14 (2%)</td>
<td>$47 (9%)</td>
</tr>
<tr>
<td>Collision or overturn</td>
<td>5,700</td>
<td>125 (60%)</td>
<td>144 (19%)</td>
<td>$38 (7%)</td>
</tr>
<tr>
<td>Smoking materials</td>
<td>2,700</td>
<td>8 (4%)</td>
<td>31 (4%)</td>
<td>$11 (2%)</td>
</tr>
</tbody>
</table>

While collisions or overturns were factors in only 4% of the automobile fires, these incidents caused three of every five (60%) automobile fire deaths. More than half (57%) of the automobile collision fire deaths resulted from fires on highways or divided highways, suggesting that these situations are more likely to occur where travel speeds are higher.

Ten percent of automobile fires were intentional; these incidents caused 11% of the deaths. Intentional fires are excluded from the remainder of the analysis of causal factors. Because the NFIRS field “cause of ignition,” includes unintentional, equipment or heat source failure, and act of nature as separate code choices, the term “non-intentional” will be used to describe all fires that were not intentionally set. During 2006-2010, fire departments responded to an estimated annual average of 136,400 non-intentional automobile fires, resulting in an average of 186 civilian deaths, 720 civilian injuries, and $424 million (US) in direct property damage per year.
How is the area of fire origin related to the cause of non-intentional automobile fires?

Table 3 and Figure 3 show that two-thirds (69%) of the non-intentional automobile fires began in the engine or running gear area, resulting in two of every five (39%) deaths. Because of their dominant share, leading factors are very similar to overall automobile fires.

Figure 4 shows the leading causal factors for non-intentional automobile fires that started in: the engine area, running gear or wheel area; the passenger area; and the fuel tank or fuel line. Figure 5 shows comparable data for automobile fire deaths. Collisions or overturns ranked first among the causal factors for deaths resulting from fires in all three areas.

Table 3. Non-intentional automobile fires, by area of origin: 2006-2010 annual averages

<table>
<thead>
<tr>
<th>Area of Origin</th>
<th>Fires</th>
<th>Civilian Deaths</th>
<th>Civilian Injuries</th>
<th>Direct Property Damage (in Millions US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle engine area, running gear or wheel area</td>
<td>93,60</td>
<td>72 (39%)</td>
<td>368 (51%)</td>
<td>$265 (62%)</td>
</tr>
<tr>
<td>Passenger area of vehicle</td>
<td>16,60</td>
<td>31 (16%)</td>
<td>132 (18%)</td>
<td>$64 (15%)</td>
</tr>
<tr>
<td>Unclassified vehicle area</td>
<td>9,10</td>
<td>39 (21%)</td>
<td>54 (7%)</td>
<td>$32 (7%)</td>
</tr>
<tr>
<td>Cargo or trunk area of vehicle</td>
<td>4,10</td>
<td>3 (2%)</td>
<td>40 (6%)</td>
<td>$13 (3%)</td>
</tr>
<tr>
<td>Exterior surface of vehicle</td>
<td>3,50</td>
<td>3 (2%)</td>
<td>19 (3%)</td>
<td>$11 (3%)</td>
</tr>
<tr>
<td>Unclassified area of origin</td>
<td>2,60</td>
<td>3 (1%)</td>
<td>5 (1%)</td>
<td>$7 (2%)</td>
</tr>
<tr>
<td>Vehicle fuel tank or fuel line</td>
<td>2,10</td>
<td>29 (15%)</td>
<td>72 (10%)</td>
<td>$10 (2%)</td>
</tr>
<tr>
<td>Other known area</td>
<td>4,60</td>
<td>7 (4%)</td>
<td>30 (4%)</td>
<td>$23 (5%)</td>
</tr>
<tr>
<td>Total</td>
<td>136,40</td>
<td>186 (100%)</td>
<td>720 (100%)</td>
<td>$424 (100%)</td>
</tr>
</tbody>
</table>

Mechanical failures or malfunctions caused three of every five (60%) of the fires beginning in the engine or running gear areas. Electrical failures or malfunctions were factors in one-quarter (24%) of the fires in these areas.

![Figure 3. Non-intentional automobile fires by leading areas of origin: 2006-2010](image)

The 12% of non-intentional automobile fires that began in the passenger area caused 16% of the fatalities. Electrical failures or malfunctions were factors in half (49%) of the fires originating in the passenger area, and mechanical failures or malfunctions were factors in 15%. Smoking materials started 8% of the passenger area fires.
Only 2% of automobile fires originated in the fuel tank or fuel line, but these fires caused 15% of the associated deaths. Mechanical failures or malfunctions were factors in half (52% of these fires) and one in five (19%) of these deaths. Leaks or breaks dominated the mechanical failure or malfunction category, accounting for one-third (32%) of the fires originating in the fuel tank or fuel line.

**Figure 5. Non-intentional automobile fire deaths, by major causal factors and areas of origin: 2006-2010**

FIRE DEPARTMENT RESPONSE TIME TO AUTOMOBILE FIRES

The time between fire occurrence and the arrival of help can play a role in the outcome. Unfortunately, most vehicles do not have a mechanism to record when a fire starts. Some fires, particularly those in rural areas, are not discovered immediately. Figure 6 shows that the response time calculated as the time elapsed between the time the alarm was received by the fire department and the time the first responding unit arrived on scene. This was calculated for all automobile fires (both intentional and non-intentional) reported in 2006-2010.

Response time was less than five minutes in 39% of the automobile fires and 22% of the deaths. The first firefighters arrived in less than 10 minutes in 85% of the fires and 71% of the deaths. Response times of ten minutes or less were seen in 82% of the automobile fires resulting from collisions or...
overturn and 64% of the associated deaths. Additional time may be spent in handling a call at a public safety answering point before the call is transmitted to the fire department.

**Figure 6. Reported automobile fires (all causes), by response time for first arriving unit: 2006-2010**

**TRENDS**

While automobile fires and associated losses still occur with distressing frequency, considerable progress has been made. The trend analysis includes both intentional and non-intentional fires. Figures 6 and 7 show that after a generally consistent downward trend, the numbers of reported automobile fires and associated fire deaths respectively were 42% and 49% lower in 2010 than in 2002. In contrast, total fires and fire deaths were only 21% and 8% lower, and structure fires and associated deaths were only 7% and 1% lower. [6]

**Figure 6. Reported automobile fires (all causes) by year**

Despite the decreases in automobile fire deaths, Figure 7 shows that in recent years, automobile fires have killed more people per year than were killed in non-residential structure fires. [2]
RISK BASED ON DISTANCE TRAVELLED

Although automobile fires accounted for 11% of reported US fires and 7% of fire deaths during 2006-2010, the risk of such an event is low in terms of the distances driven. The Federal Highway Administration published data on distances travelled. [7] Data specifically for automobiles was provided through 2008. In later years, the vehicle groupings were modified. From 2006-2008, U.S. automobiles were driven an average of 2,666 billion kilometers (1,657 million miles).

Based on 2006-2008 NHTSA data with the 2006-2010 automobile fire estimates, for every billion kilometers driven, there were

- 57 automobile fires,
- 0.08 automobile fire deaths,
- 35 non-intentional fires that began in the engine or running gear area,
- six non-intentional fires that began in the passenger area,
- two fires resting from collision or overturn, and
- 0.05 deaths from fires resulting from collision or overturn.

DATA LIMITATIONS AND ISSUES

Unknown or missing data are assumed to resemble known data. The fire statistics in this analysis are estimates. In scaling up based on the NFIRS data and in allocating unknown data proportionally, it is assumed fires that had unknown or missing data or were not reported to NFIRS would resemble the fires with reported, usable available data. Table 4 shows that the proportion of unknown or missing data varies considerably by field.

For less common events, smaller numbers can result in more volatility. The lack of complete data becomes a more serious issue when numbers are smaller. Automobile fire deaths and injuries are much less common than automobile fires. Fires caused by collisions or overturns are much less common than those caused by mechanical or electrical failures or malfunctions. The general patterns have been consistent over time but some volatility is likely due to the smaller numbers involved.
Table 4. Incidents in which the data was unknown, undetermined, left blank, or coded as "none:" 2006-2010

<table>
<thead>
<tr>
<th>Area of Origin</th>
<th>Fires</th>
<th>Civilian Deaths</th>
<th>Civilian Injuries</th>
<th>Direct Property Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile property type (all vehicles)</td>
<td>6%</td>
<td>3%</td>
<td>4%</td>
<td>10%</td>
</tr>
<tr>
<td>Cause of automobile fire</td>
<td>31%</td>
<td>39%</td>
<td>25%</td>
<td>34%</td>
</tr>
<tr>
<td>Factor contributing to automobile fire</td>
<td>58%</td>
<td>47%</td>
<td>43%</td>
<td>59%</td>
</tr>
<tr>
<td>Heat source in automobile fire</td>
<td>51%</td>
<td>54%</td>
<td>40%</td>
<td>55%</td>
</tr>
<tr>
<td>Area of origin in non-intentional automobile fire</td>
<td>12%</td>
<td>24%</td>
<td>6%</td>
<td>13%</td>
</tr>
</tbody>
</table>

NFIRS describes all types of fires and has limited vehicle-specific choices.

The NFIRS data system is used to describe all types of fires. It has a limited number of code choices that specifically relate to vehicles. Individual codes, such as area of origin code 83 – engine area, running gear or wheel area, cannot be broken down further. Very specific information about specific parts (e.g., spark plug, drive-belt, catalytic converter) involved in the ignition is generally not captured or identifiable in the coded data. Nor is the information linked to police reports or service records. The national NFIRS database does not contain information about rate of speed, vehicle inspection status, last time the vehicle was serviced, after market modifications or non-standard parts.

Although estimates of alternate fuel vehicle fires are not possible, other approaches can be used.

Vehicle power source data is also not captured. This has been particularly frustrating to those interested in tracking possible fire risks associated with vehicles using alternate fuels or power sources. Even if NFIRS had that capability, it is unlikely that the meaningful data could be available on electric vehicles until more are on the road. Table 5 shows the technology type used by automobiles on the road in 2009 and 2010. [8] In both years, alternate-fuel automobiles accounted for only 1% of the cars in use.

Table 5. Technology type used in car stock in the U.S. in 2009 and 2010. [8]

<table>
<thead>
<tr>
<th>Technology Type (in millions)</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional automobiles</td>
<td>128.74</td>
<td>126.20</td>
</tr>
<tr>
<td>Gasoline</td>
<td>128.12</td>
<td>125.47</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.62</td>
<td>0.73</td>
</tr>
<tr>
<td>Alternate fuel automobiles</td>
<td>3.18</td>
<td>3.58</td>
</tr>
<tr>
<td>Ethanol-flex fuel</td>
<td>1.71</td>
<td>1.88</td>
</tr>
<tr>
<td>100 mile electric vehicle</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Electric-gasoline hybrid</td>
<td>1.32</td>
<td>1.55</td>
</tr>
<tr>
<td>Compressed natural gas</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Compressed natural gas bi-fuel</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Liquefied petroleum gas</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Liquefied petroleum gas bi-fuel</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total automobile stock</td>
<td>131.91</td>
<td>129.77</td>
</tr>
</tbody>
</table>

Roughly 140,000 automobile fires were reported in 2009 and 135,000 in 2010. That translates to rates of one automobile fire for every 945 and 964 automobiles per year, respectively, or rates of 1,035-1,060 automobile fires per million automobiles. Estimates of conventional types of automobile fires or fires associated with other uses of similar technology can be used to develop likely fire scenarios.
Investigations of any fires that do occur can also provide valuable information. Laboratory tests can then be used to better predict the risks.

Even with the limitations discussed above, NFIRS provides sufficient detail to identify general problem areas that warrant further research and to provide general guidance to the public, manufacturers, and policy makers about how these fires might be prevented.

Anyone who works with databases from different organizations knows that scope, definitions, and sources vary based on the mission and priorities of each organization. Consequently, results may differ. Each year, the National Highway Traffic Safety Administration’s Traffic Safety Facts series, contains a table indicating the number of crashes with fire involved. In 2009, they reported 6,000 passenger car crashes with fire involved, including 527 fatal crashes. [9] Overall, 0.1% of the crashes involved fire, but fire occurred at 2.9% of the fatal crashes. NHTSA’s estimate of the number of fire-involved crashes (or collisions or overturns in this study) is fairly consistent with NFPA’s. The victim total in their analysis is much higher because they also include people who died of trauma instead of fire-related injuries only. NHTSA estimates benefit from law enforcement detail and more information about the nature of any impacts. However, NHTSA collects far less information on circumstances specific to fires.

CONCLUSIONS
While the risk of automobile fires and associated deaths is low in terms of the distance driven and progress has been made in reducing the number of automobile fires and associated deaths, more needs to be done. Losing roughly 200 people annually to these fires is unacceptable. When an automobile burns, necessary transportation is often destroyed.

Estimates derived from NFIRS and NFPA’s annual fire department survey show that the majority of automobile fires are due to mechanical or electrical problems, but three out of automobile fire deaths are due to fires that result from collisions or overturns. Research should focus on improving design to reduce the likelihood of mechanical and electrical failures over the life of the vehicle and of reducing impact-caused fires.

REFERENCES
Bus Fires in 2010-2011 in Finland

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Emergency Services College
Kuopio, Finland

ABSTRACT

The objectives of this descriptive study were to find out the information on the causes and the progress of bus fires. The aim was to find out the possibilities to improve the fire safety in the buses.

The original data on bus fires in 2010–2011 were collected by the fire departments into the national accident registry of the Finnish rescue services. Complementary data were received from the registry of the Finnish Transport Safety Agency.

Data on 126 bus fires were included in the study. Comparing to the number of buses in Finland, there were annually 5 bus fires per every 1000 registered bus. Of the bus fires 113 ignited outside the passenger area, 8 in the operator area and 2 in the passenger area. Of the fires ignited outside the passenger area 10 spread in the passenger area. Failure of the electric device was the cause of fire in 30 cases, overheated brakes or bearings in 28 cases, failure of the additional heater in 16 cases, and leaking fuel or oil in 14 cases. First extinguishers were used in 91 bus fires. Of these 78 fires were restricted or extinguished. In 7 fires, bus destroyed completely. Furthermore, 13 fires spread from the place of ignition. No fire deaths occurred but 4 persons get injured in the bus fires in 2010-2011 in Finland.

A couple of recommendations to improve fire safety in buses can be given.

KEYWORDS: bus fires, passenger safety, improvement of fire safety, recommendations

Introduction

The objective of the Internal Security Programme is for Finland to be the safest country in Europe (Government resolution, 2012). Main focus of the Programme is on safety on the daily routines. One specific objective of the Programme is to improve safety in traffic culture. Finn travels three trips and one hour a day on average. Seven percent of trips are made by bus. A risk of major accident exists, if the bus with passengers catches a fire.

The number of bus fires has increased the last 15 years in Finland. In the 2000s the average number of fire has been six per thousand buses annually. In 2009 started a national three-year project with aims at improving the statistics on bus fires and investigating their causes and progress. The final objective was to find out the possibilities to improve fire safety in buses.

Material and methods

Data on bus fires are based on PRONTO - the national accident registry on rescue services. In this project, fire investigators in each fire department collected additional bus fire specific data. Study
material was completed by the registry data on buses maintained by the Finnish Transport Safety Agency. Data were analyzed by descriptive methods.

Results

There were 57 and 69 bus fires in 2010 and in 2011 respectively. Compared to the number of registered buses, the number of fire was four per thousand in 2010 and five per thousand in 2011. In 2011, the most recent bus fire broke out in a garage destroying a total of six buses. Of these only the ignited bus is included in the following results.

Buses

About 80 percent of buses were either Scansas or Volvos made and assembled either in Sweden or in Finland. The proportion is similar to all running buses in Finland. The engine was in the rear in 86 percent, in the middle in 10 percent, and in the front in four percent of buses. Most of the buses used diesel as a fuel. Only five percent of buses were gas-operated. The average age of buses were 12,5 years. In 2011 the buses were one year older than in 2010 on average. The oldest bus was a 1993 model, and the mileage was over two million kilometers at most. Half of the buses were local buses (running within cities), quarter was long-distance buses and another quarter chartered buses.

Detection of fire

Usually (70 %) smoke was first indicator of fire. In 13 fires flames were detected same time as smoke. Flames were first indicator of fire in 27 percent of cases. Smell was first indication in 15 fires. Fire was usually (75 %) detected by the bus driver. Passenger detected smoke first nine times, flames once and smell six times. Third person detected smoke first nine times and flames six times. Most of these fires broke out in the engine department in the rear. Fire alarm system detected fire first three times.

Ignition of fire

Table 1. Bus fires by the area of origin in 2010-2011 in Finland.

<table>
<thead>
<tr>
<th>Area of Origin</th>
<th>Count (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator or Passenger Area</td>
<td>10 (8 %)</td>
</tr>
<tr>
<td>Cargo Area</td>
<td>1 (1 %)</td>
</tr>
<tr>
<td>Engine or Additional Heater Area</td>
<td>73 (60 %)</td>
</tr>
<tr>
<td>Wheel Area</td>
<td>33 (27 %)</td>
</tr>
<tr>
<td>Other</td>
<td>6 (5 %)</td>
</tr>
<tr>
<td>Unknown</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>126</td>
</tr>
</tbody>
</table>

Bus caught fire seldom in the operator area or in the passenger area (Table 1). In 2011 two fires ignited in the passenger area and none in 2010. In the operator area a total of eight buses caught fire. Over half of bus fires ignited in the engine area (50 %) or in the additional heater area (10 %). Over quarter of bus fires ignited in the wheel area. Only one bus caught fire in the cargo area in 2010-2011 in Finland. Of the fires ignited outside the passenger area 10 spread in the passenger area.

Two of the buses were set on fire (Table 2). In 14 fires ignition was localized in the engine area, but the cause of fire was not found out. The most common causes of fire can be divided into four categories: electrical failure, overheated brakes or bearings, failure of an additional heater, and fuel or oil leaks. Electrical failure caused 30 fires, including 16 fires in the engine area, nine in the operator area and two in the passenger area. The overheated brakes caused a total of 18 fires and the bearings
10 fires. Two thirds of these occurred in 2010. A total of 16 bus fires started in the additional heater area. Of these five were caused by a fuel leak. Six fuel leaks to the engine area were reported in 2011. In addition, oil leaks caused eight fires.

Table 2. Causes of bus fires in 2010-2011 in Finland.

<table>
<thead>
<tr>
<th>Cause of Fire</th>
<th>Count (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Failure</td>
<td>30 (26%)</td>
</tr>
<tr>
<td>Overheated Brakes or Bearings</td>
<td>28 (25%)</td>
</tr>
<tr>
<td>Failure of an Additional Heater</td>
<td>16 (14%)</td>
</tr>
<tr>
<td>Fuel and Oil Leaks</td>
<td>14 (12%)</td>
</tr>
<tr>
<td>Intentional</td>
<td>2 (2%)</td>
</tr>
<tr>
<td>Other</td>
<td>24 (21%)</td>
</tr>
<tr>
<td>Unknown</td>
<td>12</td>
</tr>
<tr>
<td>Total</td>
<td>126</td>
</tr>
</tbody>
</table>

First extinguishing

None of the fires was extinguished by the fixed extinguishing system. Systems are not mandatory, and therefore not common in Finland. Almost half of the fires (60 fires) were extinguished by first extinguishers (Table 3). In addition, 15 percent of fires were restricted by first extinguishing. In many cases, where first extinguishing was not tried, fire was escalated too widely.

Table 3. Effect of first extinguishing in bus fires in 2010-2011 in Finland.

<table>
<thead>
<tr>
<th>Effect of First Extinguishing</th>
<th>Count (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extinguished Fire</td>
<td>60 (48%)</td>
</tr>
<tr>
<td>Restricted Fire</td>
<td>18 (15%)</td>
</tr>
<tr>
<td>No Effect</td>
<td>13 (10%)</td>
</tr>
<tr>
<td>Not Used</td>
<td>33 (27%)</td>
</tr>
<tr>
<td>Total</td>
<td>126</td>
</tr>
</tbody>
</table>

Finnish buses are equipped with first extinguishers. Extinguishers in buses were usually (67 %) over 6 kg (13 lb) in weight. In two fires only external first extinguisher was used. First extinguishing was usually (71 fires) done by the bus driver. Two times passenger, nine times a passer-by and 16 times a fireman present before fire engine started first extinguishing.

Passenger safety

The number of passengers was known only in 69 cases (55 % of all cases). In 29 bus fires there were no passengers. In 20 bus fires the number of passengers was over 10, 62 at most. In 20 bus fires there were less than 10 passengers.

No fire deaths occurred but four people get injured in bus fires in 2010-2011 in Finland. In connection with one fire two passengers get injured. They breathed smoke. The other two injuries occurred in connection with the garage fire. Two fire fighters get injured.

In six bus fires passengers were reported to be in immediate danger. In one of these, third person assisted elderly passengers to safety. In one case a passenger had to be awakened.

Severity of damage
The bus was completely destroyed in seven fires (Table 4). Of these six occurred in 2011. Totally 13 fires were unrestricted fires, i.e. fires which spread from the area of origin. Of these 12 occurred in 2011. Almost one third of the bus fires were restricted fires, i.e. they did not spread from the area of origin. More than half of all cases (69 fires) were no more than initial fires.

Table 4. Bus fires by the severity of damage in 2010-2011 in Finland.

<table>
<thead>
<tr>
<th>Severity of Damage</th>
<th>Count (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Damage</td>
<td>22 (17%)</td>
</tr>
<tr>
<td>Initial Fire</td>
<td>47 (37%)</td>
</tr>
<tr>
<td>Restricted Fire</td>
<td>37 (29%)</td>
</tr>
<tr>
<td>Unrestricted Fire</td>
<td>13 (10%)</td>
</tr>
<tr>
<td>Completely Destroyed</td>
<td>7 (6%)</td>
</tr>
<tr>
<td>Total</td>
<td>126</td>
</tr>
</tbody>
</table>

Discussion

Based on the results received in the project, the project group has listed a couple of recommendations to improve fire safety in buses.

(i) Fixed extinguishing systems in the engine area and in the additional heater area should be maintained in buses. Their functioning should be secured.

Data on 2011 bus fires demonstrate a need of fire extinguishing systems. If the fire ignited in the engine area in the rear, the bus driver did not have time enough to put down the fire with first extinguishers. When extinguishing systems are maintained their functioning should be secured with regular service.

(ii) Buses should be furnished with two 6 kg (13 lb) first extinguishers.

Detectable bus fire has often escalated widely. Power of portable fire extinguisher is usually quite poor in such cases. It is recommended that the buses should have at least two 6 kg first extinguishers.

(iii) Hole for first extinguishing should be maintained in the engine area and in the additional heater area.

Because the power of first extinguishers is quite poor, first actions should be effective. Usually there is no time to waste in opening the engine area hatches. Almost unnoticeable holes in the hatches may help to produce more effective actions in case of the engine area fire or the additional heater area fire.

(iv) Bus and coach operators should create and put in the operation the check lists on fire risk. Check list should cover at least: engine area, fuel and oil leaks, wire bundles, electric appliances, wheels, brakes, first extinguishers and exits.

No fire is the best situation. All the preventive actions are needed to improve bus fire safety. Check list on fire risk is useful tool to prevent bus fires. Check lists and the use of them should be entrenched in the regular service. A couple of the bus fires studied could have been prevented with the careful checking in the regular service.

(v) Bus and coach operators should arrange regular theoretical and practical training on identifying fire risks, first extinguishing and evacuation of passengers for their personnel.

(vi) Topics on fire safety should be included in all mandatory refresher courses of bus drivers. Bus fire is a rare event. Good preparing for the exceptional situations can be obtained by practicing. In the cases analyzed, there were situations where the skills of the bus drivers were not superior in case of fire.

(vii) The investigation of bus fires and the reporting of investigation should be improved.
Even if bus fire is a rare event, there is always the possibility of major accident. The risk of a fatal bus fire is not exceptional in Finland. Therefore more information on ignition and progress of bus fires are needed. To get this information co-operation between public authorities, bus and coach operators and insurance companies are needed. Although the current situation in bus fire investigation is good, the information should be gathered better, more comprehensive, more widely and with higher quality.

Acknowledgements

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Motorcoach Fire Safety Analysis: The Causes, Frequency, and Severity of Motorcoach Fires in the United States

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Abstract:

The Federal Motor Carrier Safety Administration’s (FMCSA) mission is to reduce crashes, injuries, and fatalities on our nation’s roads involving motor vehicles, and to further its work the agency set out to identify ways to reduce motorcoach fire risk. FMCSA’s Vehicle and Roadside Operations Division contracted the Volpe National Transportation Systems Center to perform a study to collect and analyze information from government, industry, and media sources on the causes, frequency, and severity of motorcoach fires in the United States, and to identify potential risk reduction measures. Volpe Center analysts only considered fires that were mechanical or electrical in origin, and that were neither the result of a collision nor arson. This study establishes an integrated incident database, allowing for a comprehensive analysis of risk trends and patterns, and provides recommendations that could result in fewer motorcoach fires and, in turn, safer roads and lives saved.

Volpe Center analysts created a database on reported motorcoach fire incidents between 1995 and 2008 as a basis for the study. The resulting database consists of 899 records from the sources cited below spanning the years 1995–2008, with the 2004–2006 data being the most complete. Analysts constructed the database to facilitate analysis by location of origin, point of ignition, geographic and vehicle characteristics, inspection and maintenance histories, vehicle damage, and human injuries and fatalities.

The data sources for this study included the U.S. Fire Administration’s (USFA) National Fire Incident Reporting System (NFIRS), FMCSA’s Motor Carrier Management Information System (MCMIS), the National Highway Traffic Safety Administration’s (NHTSA) State Data System (SDS), and NHTSA’s Fatality Analysis Reporting System (FARS). R.L. Polk and Co. provided summaries of motorcoach registrations and detailed characteristics data. Additional motorcoach fire records were compiled by two major carriers and two insurance firms. Volpe Center analysts used independent sources to verify that incidents were applicable, to address missing or unknown field values, and to derive non-reported elements.

Some of the key findings from the study include:

- Motorcoach fires have occurred with an approximate frequency of 160 per year, based on the most complete and current reporting years.
- Although a single catastrophic motorcoach fire resulted in 23 fatalities and 15 injuries, approximately 95 percent of the reported fires over the study period resulted in no direct injuries and fatalities.
- The most frequently identified location of fire origin was the engine compartment, followed closely by wheel wells. Together they comprise about 70 percent of reported fires.
- The most frequently specified points of ignition were the brakes, turbocharger, tires, electrical system, and wheel/hub bearings.
- The frequency of fires on motorcoaches of model years 1998–2002 relative to older models was disproportionately greater than their relative populations.
Vehicle out-of-service (OOS) rates for fire-involved motorcoaches have exceeded those for all buses, and the gap has widened in recent years.

Analysis of inspection data suggests that the frequency of roadside inspections with OOS violations may be an indicator of future motorcoach fire risk.

Current North American Standard Motor Carrier Inspection and OOS criteria may not sufficiently identify all precursors of motorcoach fires.

These findings have important implications for reducing risk of motorcoach fires through improvements in data quality, inspection and enforcement, and vehicle and equipment design and training. With these improvements, research should continue efforts to identify critical inspection items associated with fire risk. Further recommendations include exploring the use of focused fire safety investigations and the development of wheel-well fire detection/suppression systems.

KEYWORDS: motorcoach, passenger carriers, fire safety, risk analysis, fire detection systems, fire suppression systems, passenger vehicle inspection, motorcoach maintenance, NFIRS, MCMIS

INTRODUCTION

As part of the Federal Motor Carrier Safety Administration’s (FMCSA) mission to reduce motor-vehicle-related injuries and fatalities on our nation’s roads, the agency set out to develop a profile of motorcoach fire risk and how it can be mitigated.

Federal agencies, industry, and the media have conducted research to shape a reliable, albeit general profile of bus fires, but motorcoach-specific fire data have not been so easily accessible. Neither a single, comprehensive, nationwide motorcoach fire database exists nor have other databases been designed to target this population. To expand the current body of research and lay the groundwork for such a database, FMCSA commissioned the Volpe National Transportation Systems Center (Volpe Center) to collect and analyze information from government, industry, and media sources on the causes, frequency, and severity of motorcoach fires and to identify potential risk reduction measures.

This study created an integrated Motorcoach Fire (MCF) database of reported fires between 1995 and 2008 as a basis for this profile. The database focused on spontaneous, for-hire motorcoach fires caused by electrical and mechanical failures. Fires caused by collisions with other vehicles and fixed objects were excluded from this study, as were those that resulted from passenger activity such as smoking or arson. The resulting MCF database consists of 899 records from the years 1995–2008, with the 2004–2006 data being the most complete. The database constructed facilitated analysis by location of origin, point of ignition, geographic and vehicle characteristics, inspection and maintenance histories, vehicle damage, and human injuries and fatalities.

The remainder of this paper presents the background information that formed the basis for this study, the development of the Volpe Center MCF database, and a discussion of key findings, including ways to prevent motorcoach fires and reduce their severity. The paper includes the following sections:

Background and Scope – outlines background information on motorcoach fires, including known causes, trends, and best practices that formed the basis for the study’s data collection and compilation and analysis.

Data Collection and Compilation – summarizes the development of the MCF database, including a list of the data sources used and the methods for the collection, reduction, and validation of data.

Analysis – presents the analysis methodology and a discussion of the key findings.

Recommendations – provides direction for further development of data and countermeasures to reduce the risk of motorcoach fires.
BACKGROUND AND SCOPE

The following discussion presents an overview of the causes, frequency, and severity of motorcoach fires based on information obtained from seven recently published bus fire studies, reports, and interviews. For a complete, annotated list of these studies, consult the FMCSA project study report [1].

Overall, the literature on motorcoach fire risk cites a variety of common contributing factors to motorcoach fires, ranging from mechanical and electrical failures, overheating, combustible and non-retardant materials, to all of the demands placed on the driver. (For example, see [2, 3].) Engineering forensic studies indicate that the two most common ignition sources responsible for motorcoach fires are spark ignition and auto ignition. (For example, see [4].) Spark ignition can occur when a spark encounters the proper mixture of combustible material and air, whereas auto ignition can result when a combustible material heats to its auto ignition temperature. Motorcoaches contain a large variety of combustible materials, such as rubber, plastic, and fluids. These materials are typically located in the engine compartment, fuel system, bus interior, and wheel wells. For detailed catalogues of the locations and conditions under which different ignition sources and combustible materials may coincide, refer to Table 1 and Table 2 [5].

The frequency of motorcoach fires in the U.S. has been harder to discern with confidence. The National Fire Prevention Association has estimated that the average frequency of motorcoach fires may be as high as six per day, but this figure includes transit buses, school buses, large vans, trackless trolleys, and motorcoaches [6]. Reliable estimates of motorcoach fire frequency do not exist for this study period because data collection organizations have not standardized the classification of motorcoach-only fires.

Whatever their actual frequency, the severity and consequences of motorcoach fires vary significantly, but can be disastrous. A motorcoach fire can consume a vehicle within 15 to 20 minutes, causing property damage ranging in cost from tens of thousands of dollars up to the replacement value of the bus – the average of which was estimated in 2008 to be $450,000 [7]. Yet passenger injuries and fatalities due to fire are rare. In the vast majority of reported cases, passengers were able to evacuate the motorcoach safely, avoiding deaths and injuries. In spite of this fact, the Global Limo bus fire near Wilmer, TX in 2005 [8], which resulted in 23 fatalities and 15 injuries, stands out as an unprecedented example of the potential human toll of a motorcoach fire.

Recognized Countermeasures

The major stakeholders in commercial motor carrier safety are well-positioned to address important aspects of the motorcoach fire safety problem. Federal agencies develop and enforce safety standards and regulations. States cooperate with the Federal government in conducting inspections, taking enforcement actions, and setting inspection procedures and out-of-service (OOS) criteria through the Commercial Vehicle Safety Alliance (CVSA), a nonprofit organization of State, Provincial, and Federal officials in the U.S., Canada, and Mexico. CVSA and other international organizations also provide a variety of educational materials and guidance for operators and drivers to minimize the fire risk on increasingly complex equipment. (For example, see [9, 10].) Carriers, manufacturers, and their industry associations often cooperate voluntarily in identifying solutions for safety-related problems and best practices for training carriers’ staff. All of these stakeholders play a significant role in developing uniform standards and best practices for motorcoach fire safety.

Many different practices contribute to fire safety, from preventing fires through proper vehicle maintenance to safely evacuating passengers during an emergency. Types of practices frequently cited for their effectiveness in preventing, reducing the severity, and mitigating the consequences of motorcoach fires include: using fire-resistant materials to prevent the spread of fires from the point of ignition; installing automatic warning systems to detect equipment failures and fires; conducting pre-
trip inspections to identify and repair any vehicle safety issues; and implementing safety management
processes to provide maintenance staff and company inspectors with the knowledge and skills to
identify and address motorcoach conditions that can lead to fires. (For example, see [11].)

DATA COLLECTION AND COMPILATION

Although credible, aggregate estimates of all types of bus fires exist, motorcoach-specific estimates
are not easily accessible in State and Federal accident statistics, national fire databases, and general
media sources. To improve and facilitate targeted analysis, the Volpe Center analysts created a MCF
database comprised of motorcoach fire incidents from 1995–2008 as a basis for this study. The
resulting MCF database consists of 899 records from the sources cited below spanning the years
1995–2008, with the 2004–2006 data being the most complete. Analysts constructed the database to
facilitate analysis by location of origin, point of ignition, geographic and vehicle characteristics,
inspection and maintenance histories, vehicle damage, and human injuries and fatalities.

The U.S. Fire Administration’s National Fire Incident Reporting System (NFIRS) database and
FMCSA’s Motor Carrier Management Information System (MCMIS) database both served as primary
data sources for this study due to their breadth of motorcoach incident records. Additional data
sources used include: the National Highway Traffic Safety Administration's (NHTSA) Fatality
Analysis Reporting System (FARS); NHTSA’s State Data System (SDS); NHTSA’s vehicle defect
database; the joint FMCSA and NHTSA bus fire analysis database; and State police accident reports,
State DOT bulletins, and news reports. Analysts obtained vehicle mileage data from the Federal
Highway Administration’s highway statistics charts and motorcoach population and characteristics
data from R.L. Polk and Co. Two major carriers and two insurance firms provided additional
motorcoach fire records.

The Volpe MCF database was created through a multi-step process, which involved: (1) querying the
national public and industry data sources listed above for motorcoach fires; (2) verifying and
classifying the query results; (3) obtaining and analyzing State police accident reports; (4) filling in
missing, unknown field values or unreported elements with the details available from the NFIRS
“Remarks” field and police and media reports; (5) corroborating each vehicle and carrier represented
in the data with inspection and review histories from FMCSA’s MCMIS database; and (6) removing
any Personally Identifiable Information from the resulting dataset. See Tables 9 and 10 in the full
project study report [12] for a more detailed explanation of the data development process, the
resulting numbers of incident records populated by data source, and the number of records missing
values in key analysis fields.

The MCF database combines several data sources and therefore it inherits some of their limitations,
including geographic and temporal skewing of data and, in some instances, issues with data
completeness and quality. NFIRS provided the most extensive coverage and depth, but inherently
lacks the precision of data on vehicle fires because it was structured for the reporting of fixed property
fires. For example, the field values for identifying the vehicle as a motorcoach, i.e., Vehicle
Identification Number (VIN), vehicle make, and vehicle model), are often conflicting, incomplete, or
missing altogether, and there is no field for identifying the motor carrier. MCMIS, primarily a police
accident reporting system, reliably identifies the motorcoach and its operator when there has been a
collision. However, spontaneous fires or those attended to by fire departments only often go
unreported in MCMIS even when they meet the ‘crash’ reporting criteria. Workarounds for
overcoming some of these limitations were developed by matching common fields from multiple data
sources and by using other reference sources. Nevertheless, the resulting coverage of applicable
events and accuracy of key analysis fields were limited by the assumptions made in the process.

ANALYSIS
This study seeks to provide an informed basis for assessing the problem of motorcoach fires in the U.S. and for evaluating recommendations in terms of their preventive value and potential for reducing any consequences. Given the breadth of the incident records and related data on fires, carriers, and involved vehicles, the MCF database is suitable for such analyses.

For trend and causal analyses to be valid, data must be representative, accurate, and complete within estimated levels of confidence. This requires a determination of the minimum sample sizes and quality levels for each data source and entity. While such rigorous statistical analysis exceeds the scope of this study, Volpe analysts examined a subset of fields from the database, considered sufficiently populated to assess the relationships between various motorcoach fire risk factors. A variety of data sources contribute to these data fields. More than half of the 899 identified motorcoach fire records populate these data fields. However, nearly every field draws on a variety of data sources. No single record contains data in every field, and less than one-third of these records have specified values in six or more fields.

Considering these issues with data quality, the analysis uses the most complete data fields to focus on the following areas: incident identification, equipment characteristics, and fire severity. The most populated data fields include: data, State, VIN, vehicle make, model, year, engine manufacturer and model, direct casualties, and property damage. Additional fields were derived to analyze fire origin, ignition points, and warning suppression systems.

Summary of Findings

Geographic Distribution

Seventy percent (627) of the records in the MCF database list the State in which the fire occurred. The most complete study period, 2004–2006, contains 15 States with the highest ratios of fire incident records relative to highway vehicle miles traveled (VMT). Eastern and Western regions each contain six of these records. The South follows with two records, and the Midwest with one record. For raw counts of motorcoach fire records by State, region, and highway VMT, see Table 12 and Table 13 in the complete project report [13].

Care must be taken in drawing conclusions regarding statewide or regional motorcoach fire risk from these distributions. An accurate portrait of State motorcoach fire risk must take a variety of additional factors into account. States with the highest fire incident record counts relative to VMT may reflect more thorough reporting standards and/or a confluence of data sources. An omission in reporting one or two incidents over a three-year period in a State with few reported incidents could also easily change its ranking. For this reason, in further analyses of geographic influence, it might be prudent to focus on States already reporting a significant number of incidents. These rates may also be skewed by the wide variability of motorcoach travel in proportion to applicable highway vehicle travel. For instance, Eastern States with greater population and route densities may incur more motorcoach VMT per highway than less populous States.

Frequency

Industry sources have estimated that motorcoach fires occur nationwide on at least a daily basis. However, the reported data compiled in the MCF database indicates a much lower rate. The most current and complete study period, 2004–2006, indicates about 160 reported motorcoach fires per year. Only 229 fires were reported from 1995–2003, resulting in an even lower annual average of 25. This lower rate reflects incomplete data for the earlier portion of the study period.

On the basis of current reporting, the MCF database shows no indication that the frequency of motorcoach fires is significantly increasing or decreasing. Recent annual averages support this finding. The years 2007–2008 show an average annual total of fire incident records less than 100; this number is comparable to that of the 2004–2006 average due to delays in incident reporting or verification by published reference sources. If this trend continues, another data collection phase
ending in 2010 would be expected to yield an additional 190 records for the years 2007–2008, resulting in a relatively constant annual count of about 160 records for 2004–2008.

However, actual fire occurrence may be far greater than the number of records collected per year would suggest. Reporting criteria for motorcoach fires are less clear and less enforceable compared with the criteria for other types of roadway incident reporting. For instance, a fire that is extinguished before it causes injury or that does not meet some arbitrary threshold of monetary damages is less likely to be documented to employers, insurance companies, or government authorities. Fires that occur on private property, in parking areas, or involve an OOS vehicle are also less likely to be publicly reported. It is understandable that fires that meet the towaway criteria (for reporting to MCMIS) but otherwise go unnoticed by the public would not be reported.

Even if reporting criteria could be enforced, the data compilation process outlined above still filters out an undetermined number of applicable fire incident records, such as those that do not have field values or reference data that accurately identify the involved vehicle as a motorcoach. The MCF database only provides a sample of verifiable incident records, not all reported incidents. Accordingly, this study can only project that complete and accurate reporting by all sources would yield an average occurrence rate of at least 160 fires per year.

**Severity**

The average severity of motorcoach fires appears small compared to rare, disastrous incidents such as the Global Limo fire. Approximately 96 percent of the reported fires did not result in injuries or fatalities. Altogether, the data sources provided 28 fire records (3.6 percent) with values other than blank or zero for the injury and fatality fields. One of these was the Global Limo fire, which alone resulted in 15 injuries and 23 fatalities. Twenty-six fire records contained between one and three injuries (a total of 36 injuries) and no fatalities, and one fire record cited one fatality with no other injuries. Discounting the Global Limo fire and extrapolating this sample for all of the records in the database, one would expect to find 32 fire records, each citing between one and three injuries and fatalities, for a projected total of 42 injuries and fatalities.

Property damage proved similarly variable. NFIRS, one insurance company, and one carrier provided the 210 fire records with property damage estimates. For all of these sources, the positive-value damages range from $100 to $400,000, with a mean value of $64,647 and a median of $31,548. The ranges and averages vary significantly between sources. NFIRS contains damage values for 151 of the 210 records and shows losses over the entire range, with a mean value of $51,076 and a median of $6,500. For statistics on comparable damages from the applicable data sources, consult Table 11 in the project study report [14]. Total losses from those reported fires amount to about $8.2 million.

Actual severity counts may be higher than the recorded values suggest, as they are often ambiguous or difficult to verify.
Fire Origin

For the most complete study years, 2004–2006 (Figure 1), the MCF database shows that the two most common origin locations of reported fires were the engine compartment and the wheel well, with each contributing about 35 percent of the fires respectively, and 10 of the 12 fires resulting in direct injuries and/or fatalities. Only nine fires originated in the engine or fuel system. However, due to the variation amongst data sources and the ambiguity of blank and zero values, there is no clear distribution of average damages per fire.

Specific Ignition Point

Figure 2  Reported ignition points, 1995–2008.
As shown above in Figure 2, the most frequently identified points of ignition were brakes, tires, turbochargers, wheel bearings, and electrical sources in the engine, which accounted for 66 percent of the reported ignition points. Other wheel-related, fluid, and electrical system ignition points contributed an additional 24 percent. Only eight fire records, or 2 percent of the reported fires, specifically identified exhaust systems.

**Model Year and Vehicle Age**

![Fire Records by Model Year for Year of Incident](image)

*Figure 3 Fire records by model year, 2004–2006.*

Figure 3 demonstrates that for the most complete study period, 2004–2006, more than 50 percent of the incident records involve motorcoaches with model years 1998–2002. These motorcoaches not only had a higher reported frequency of fire occurrences, but also a substantially higher reported incident rate relative to their peers than older motorcoaches. More powerful engines with higher fuel efficiency and lower emissions may have contributed to an increase in engine fires in 1998 and later-model-year engines.

**Vehicle Make and Model**

Volpe analysts calculated the rate of fire incidents for specific vehicle makes and models by dividing by the number of fires and the number of vehicles in service at the time of the fires. Application of the R.L. Polk 2006 national vehicle registration data to the core incident years suggests that manufacturers’ exposure to fire incidents correlates with the number of vehicles of that make in operation. Sample sizes of incidents for individual models are too small to make a similar observation.
**Vehicle OOS Rate as Fire Risk Indicator**

Figure 4 above shows for the years 2003–2007 an increasing vehicle OOS rate for motorcoaches involved in a fire subsequent to an inspection. This trend may indicate vehicle maintenance and repair issues in those motorcoaches prone to fires. However, analysis of all motorcoach OOS rates shows that the OOS rate for any group of inspected motorcoaches is an indicator of future fire risk. Furthermore, diverging rates for involved versus non-involved vehicles over the last five-year inspection point to the growing risk of motorcoach fires. Given additional years of inspection data, one could infer potential benefits of targeting motorcoaches and carriers that have high occurrences of vehicle-related violations in order to identify specific fire risk factors.
**Carrier Safety Ratings as Fire Risk Indicator**

*Table 1: Compliance review (CR) ratings for 161 carriers in the MCF database.*

<table>
<thead>
<tr>
<th>Safety Rating Level</th>
<th>Factor 3 Rating: Operational</th>
<th>Factor 4 Rating: Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfactory</td>
<td>407</td>
<td>398</td>
</tr>
<tr>
<td>Conditional</td>
<td>8</td>
<td>69</td>
</tr>
<tr>
<td>Unsatisfactory</td>
<td>64</td>
<td>12</td>
</tr>
<tr>
<td>No rating</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>488</strong></td>
<td><strong>488</strong></td>
</tr>
</tbody>
</table>

Table 1 above shows the safety ratings given to 161 carriers, identified in the MCF database over the course of 488 CRs conducted between 1990 and 2008. The majority of the carriers received satisfactory ratings. Relatively few carriers obtained less than satisfactory ratings (e.g., conditional or unsatisfactory), but those that did accounted for the majority of the Operational and Vehicle causal factors. However, these percentages are approximately the same as for all passenger-carrier reviews in the 2003–2007 period: 15.4 percent of all passenger carrier ratings were less than satisfactory for Factor 3 and 17.5 percent, for Factor 4.

Compliance ratings of fire-involved motorcoach carriers show no apparent association with higher levels of deficiencies in a carrier’s own inspection, repair, and maintenance practices. However, this may be more a reflection of current deficiencies in the assessment standards than actual differences in practices for fire safety. The number of violations related to inspection, repair, and maintenance found in CRs for all carriers is low, particularly for violations not primarily recordkeeping in nature.

**OOS Criteria**

In the past few years, there have been major additions to the North American Standard OOS criteria regarding inspection of major engine electrical components and wheel hubs and bearings, two main origin locations of motorcoach fires. However, this study found that important fire origin locations and ignition points, such as auxiliary electrical systems, air conditioners, and turbochargers, have not yet been addressed as vehicle inspection items. In addition, inspection items involving brakes, tires, and fuel and exhaust systems may need a more in-depth review to determine if enhanced inspection criteria might be implemented for motorcoaches.

**Fire Warning and Suppression Systems**

Failure detection systems, currently available for tire and turbocharger malfunctions, could prevent 42 percent of all motorcoach fires. Engine-compartment detection/suppression systems could help to reduce the risk of 36 percent of all motorcoach fires. If used together on every motorcoach, they might be able to prevent or reduce the consequences of wheel-well and engine fires, which account for 70 percent of all fires in the MCF database. The introduction of these systems in 2004 saw a potential for the major manufacturers to provide them for more than 10 percent of the entire U.S. motorcoach fleet by 2008. Although studies have projected that these failure detection systems will only marginally reduce injuries and fatalities, they could provide life-saving benefits for a rare catastrophe, such as the Wilmer bus fire.
RECOMMENDATIONS

Analysis of the literature and data on motorcoach fire risk supports recommendations to FMCSA, other agencies, and the passenger carrier industry in the areas of data quality and reporting; compliance inspection and review standards; vehicle inspection, repair, and maintenance; vehicle design, equipment development, and operational training; and directions for future study. At the level of data collection, standardization and collaboration with other data source organizations will be integral to developing and maintaining a robust dataset of motorcoach fire incidents. This analysis further suggests that current vehicle inspection standards and CR practices could be strengthened to provide greater focus on issues related to fire safety. While significant progress has been made in recent years, roadside inspection criteria may be further revised to include more fire precursors.

Research in the field should continue efforts to identify critical inspection items associated with fire risk. Recommended areas of exploration include the use of vehicle OOS rates as an indicator for focused fire safety investigations, the development of wheel-well fire detection/suppression systems, and methods to enhance fire-response equipment, fire safety procedures, and training requirements.

REFERENCE LIST

12. Ibid., 32.
13. Ibid., 33-34.
Risk of Commercial Truck Fires in the United States: An Exploratory Data Analysis

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John A. Volpe National Transportation Systems Center, U.S. Department of Transportation Research and Innovative Technology Administration, Cambridge, Massachusetts, United States

ABSTRACT:

Large trucks are involved in only 8 percent of fatal crashes per year, but 17 percent of fatal fires. The scope of the current body of research is limited. Studies have treated truck fires generally as a subset of vehicle fires or in their own right on a smaller scale, confined to a limited pool of data. This study, commissioned by the Volpe National Transportation Systems Center (Volpe Center) for the Federal Motor Carrier Safety Administration (FMCSA), expands the current body of research to collect and analyze information from government, industry, and media sources on the magnitude, trends, and causes of truck fires in the United States and to identify potential risk-reduction measures.

This study succeeds FMCSA’s Motorcoach Fire Safety Analysis (2009), furthering the agency’s mission to improve commercial motor vehicle (CMV) safety on our nation’s roads. Focusing on non-passenger CMVs with a Gross Vehicle Weight Rating (GVWR) of Class 4 and above, this study combines several government and industry data sources to investigate potential causal relationships across truck fire incidents, crash rates, and fatalities.

For this study, the Volpe Center developed several relatable databases of reported truck fire incidents between 2003 and 2008. These include 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) Fatal Incident Reporting System (FARS) database. To obtain a preliminary representation of truck fire incidents, Volpe Center analysts matched data points across multiple datasets. The Volpe Center organized the resulting databases to facilitate analysis by geographic distribution, vehicle characteristics, fire origin, incident characteristics, and inspection and crash histories.

This study found that CMV fires are most common among GVWR Class 8 trucks with the frequency of truck fire fatalities six times greater than that of other motor vehicles. This figure is high, but when examined in conjunction with crash, inspection, and vehicle data, it offers insight into new areas of research. For example, analysis indicates that truck fires occur more often in the days following a crash. Trucks with compliance issues are also much more susceptible to fires. The truck is the striking vehicle in the majority of fatal fires. This portrait of truck fires may have significant implications for the future direction of truck fire safety.

KEYWORDS: CMV, commercial truck, motor carriers, fire safety, risk analysis, vehicle inspection, vehicle maintenance, NFIRS, MCMIS, TIFA, FARS, NFPA
INTRODUCTION

This paper documents the Federal Motor Carrier Safety Administration’s (FMCSA) ongoing study conducted by the Volpe National Transportation Systems Center (Volpe Center) to assess the nature and severity of commercial truck fires in the United States. The agency has recognized that commercial truck fires have been under-researched even though they represent a significant threat to safety on our nation’s roads. This study contributes to fulfilling that need and aims to further FMCSA’s mission to improve highway safety by developing a comprehensive portrait of commercial truck fire trends using available data and analysis approaches. The insights gained through these findings and methodological approaches will not only inform existing recommendations for reducing the risk of commercial truck fires but will also aid in identifying new safety measures.

A preliminary data search reveals compelling comparisons of large truck (freight vehicles weighing greater than 10,000 lbs.) fire risk and crash risk of large trucks relative to all highway vehicles. As a well-studied phenomenon, crash risk provides a solid comparative baseline for fire risk. Aggregate data from published U.S. Department of Transportation (U.S. DOT) sources indicate that the rate of fatalities from large truck fires far outweighs their presence on our roads, to a greater degree than fatalities from crashes (see Table 1).

Table 1 2002-2007 annual average of vehicles registered and incident fatalities by vehicle type, vehicles registered fatalities from crashes, and fatalities from fires.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Vehicles Registered (BTS)</th>
<th>Fatalities from Crashes (NHTSA)</th>
<th>Fatalities from Fires (NFPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Highway Vehicles</td>
<td>248,059,515</td>
<td>42,639</td>
<td>441</td>
</tr>
<tr>
<td>Large Trucks</td>
<td>9,142,425</td>
<td>5,038</td>
<td>68</td>
</tr>
<tr>
<td>% Large Trucks / All High</td>
<td>3.7</td>
<td>11.8</td>
<td>15.4</td>
</tr>
</tbody>
</table>
| Highway Vehicles           |                          |                                | Source: Bureau of Transportation Statistics (BTS) [1]; National Highway Traffic Safety Administration (NHTSA) [2]; National Fire Prevention Association (NFPA) [3]

On average, in 2003–2007, large trucks only accounted for 3.7 percent of all highway vehicles registered. Yet out of this pool of highway vehicles, they represented 11.8 percent of all fatal crashes, and, according to the National Fire Prevention Association (NFPA), an even more disproportionate 15.4 percent of fatal fires. The rate of fatal commercial truck fires is nearly four times the percentage of commercial trucks registered. These figures demonstrate that despite relatively low numbers, fire incidents involving large trucks pose a significant safety risk on the nation’s highways, a proportionally greater risk than crash incidents without fire.

Since the scope of this study is limited to commercial trucks, a major challenge was extracting data involving only those trucks operating commercially. Some vehicles of Gross Vehicle Weight Rating (GVWR) Class 3 (10,001-14,000 lbs.) do not operate commercially, and are difficult to distinguish in the available datasets. Therefore, this paper focuses on known commercial trucks defined as GVWR Class 4-8 vehicles. In addition, Volpe Center analysts drew on a larger range of data sources for this study than were previously used in the Motorcoach Fire Safety Analysis [4] and the Preliminary CMV Fire Analysis [5] to explore a variety of topics on the risk of commercial truck fires. These topics address (a) the magnitude and severity of commercial truck fires between 2003–2008; (b) the characteristics that carriers, drivers, and vehicles involved in fire incidents may share; and (c) the contributing factors behind crash and non-crash fires, and fatal and non-fatal fires.

The remainder of this paper discusses data sources used for the study, approaches used to refine the data, results from analysis of key topics, and recommendations for enhancing this research.
DATA SOURCES AND DATA DEVELOPMENT

Establishing a national database on reported fire incidents has proven a difficult task for many researchers. For example, from 1996–1998 General Motors (GM) sponsored a series of analyses using government-maintained field collision data files, concluding that “existing sources contain insufficient information to satisfactorily understand the causes of motor vehicle fires” [6]. For the Motorcoach Fire Analysis [4] study, Volpe researchers were confounded by many of the same limitations cited by GM, but were able to fill in the gaps with other sources of information because of the publicity generated by a relatively small number of ‘newsworthy’ motorcoach fire incidents. This commercial truck fire study relied on primary field sources supplemented by a number of secondary sources to identify and verify the relevant incidents, and attributed values for the entities related to those incidents. These data sources are described below.

Primary Data Sources

The National Fire Incident Reporting System
The National Fire Incident Reporting System (NFIRS) is a nationwide database managed by the National Fire Data Center (NFDC) within the U.S. Department of Homeland Security, the Federal Emergency Management Agency, and the U.S. Fire Administration. NFIRS tracks and records data about all fire station-reported fires in the U.S. This includes structural fires in addition to the vehicular fires of interest to this study. NFIRS also provided a remarks field for select fire records, which may provide additional specifics about the fire record. NFDC originally designed this database as a tool to aid U.S. fire departments in the development of uniform fire reporting and data analysis practices.

Motor Carrier Management Information System
The Motor Carrier Management Information System (MCMIS) is a database administered by FMCSA, which stores commercial motor vehicle (CMV) census data and historical crash, inspection, and compliance review records. MCMIS contains census data on commercial motor carriers, including the type, the number of drivers, and number of power units.

Trucks Involved in Fatal Accidents
Trucks Involved in Fatal Accidents (TIFA) from the University of Michigan’s Transportation Research Institute is a database that expands on National Highway Traffic Safety Administration’s (NHTSA’s) Fatal Accident Reporting System (FARS). FARS provides nationwide census data regarding fatal injuries from motor vehicle traffic crashes. TIFA supplements FARS medium and heavy truck records by including interviews with first responders, such as personnel from fire, police departments, and the admitting hospital. A typical TIFA entry contains basic information describing the incident, the people, and vehicles involved, and the vehicle damage and fatal injuries sustained by all parties.

Supplemental Data Sources

U.S. Vehicle Fire Trends and Patterns (National Fire Protection Association)
“U.S. Vehicle Fire Trends and Patterns” [7] is a periodic research report containing updated summary statistics on fire incidents involving transportation vehicles of all modes as well as more detailed statistics on highway vehicle fires. This report tabulates counts of incidents by year and distributions by vehicle types and variables representing contributing and occurrence factors. These numbers are total estimates for the U.S. based on NFIRS data and the NFPA’s annual survey of fire departments.

Large Truck Crash Causation Study
The Large Truck Crash Causation Study [8], developed jointly by FMCSA and NHTSA, created a highly detailed study of a small number of CMV crashes. The study draws on a nationally representative sample of crashes involving CMV with GVWR 10,001+ pounds, and that resulted in at least one fatality or injury.
Vehicle Registration Data (R.L. Polk and Company)
R.L. Polk and Company is a private data collection and reporting firm, specializing in a wide range of automotive and commercial vehicle data. Specifically, its dataset contains directly applicable data on the vehicle population by GVWR, model, model year, and manufacturer. These figures provide a measure of exposure/normalization for CMV fires. These records allow stratification by vehicle make, model, and year.

FHWA Highway Statistics

Data Development
Several of the primary datasets for this research required significant refinement in the Oracle database prior to analysis. This development process pared the data down to only the records relevant for commercial truck research. This research focused on fires from the appropriate time period, from known large truck types, and trucks used by for-hire trucking companies and private commercial carriers. To that end, records were restricted by the analysis period (2003–2008), vehicle size (GVWR Class 4-8), and known CMV make/model. To the extent possible duplicate records were also eliminated from consideration.

TIFA and MCMIS required little additional development to identify applicable records. Out of all the primary data sets, NFIRS required the most involved refinement process, reducing the NFIRS dataset from 91,401 to a final count of 32,747 fires for analysis. The most time-consuming step involved identifying vehicle makes and models (a) translated from Vehicle Identification Numbers (VIN), and (b) identified by the firefighter at the scene. VINs and vehicle models were extrapolated in cases where the field value was unknown, a process that identified several thousand additional fire records suitable for analysis in this study.

ANALYSIS

Overall Magnitude and Trends

Over the study period, the risks associated with large commercial truck fires were significant when compared to other components of highway vehicle safety risk.

Table 2 shows that commercial trucks pose a significant fire safety risk on the nation’s highways, disproportionally higher than commercial truck crash risk. Large commercial trucks account for about 7,000 fires annually, but less than 3 percent of fires involving all highway vehicles. These totals are less than would be predicted by the proportion of crashes and other measures of exposure. However, fatal fires involving commercial trucks represent 17 percent of all fatal highway fire incidents, and more than twice the proportion of all fatal crash incidents.
Table 2  Comparison of crashes and fires for all motor vehicles and commercial trucks.

<table>
<thead>
<tr>
<th></th>
<th>2003–2008 Annual Averages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Vehicles Registered (Thousands)</td>
</tr>
<tr>
<td>All Highway Vehicles</td>
<td>246,478(^a)</td>
</tr>
<tr>
<td>Commercial Trucks</td>
<td>8,544(^a)</td>
</tr>
<tr>
<td>Percentage Involving Commercial Trucks</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

*Vehicle Miles Traveled (VMT); Sources: (a) FARS; (b) U.S. Vehicles Fire Trends and Patterns; (c) BTS; (d) MCMIS (e) TIFA; (f) Estimates from data development

**Gross Vehicle Weight**

Class 8 vehicles are involved in more fires and more fatal fires than any other class of vehicles greater than 14,000 lbs. GVWR. They also are involved in over twice the rate of fatal fires of any other weight class.

Table 3 presents the number and rates of vehicle fires and fatal fires by GVWR from 2003–2008 using data from the NFIRS and the TIFA databases.

Table 3  Fires and fatal fires by GVWR class from 2003–2008.

<table>
<thead>
<tr>
<th>GVWR Class</th>
<th>GVWR Weight Range</th>
<th>Number of Fire Incidents(^a)</th>
<th>Fires per Billion Miles Traveled (VMT)(^c)</th>
<th>Number of Fatal Fire Incidents(^b)</th>
<th>Fires per Billion Miles Traveled (VMT)(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>14,001-16,000 lbs.</td>
<td>1,810</td>
<td>19</td>
<td>12</td>
<td>0.13</td>
</tr>
<tr>
<td>5</td>
<td>16,001-19,500 lbs.</td>
<td>950</td>
<td>21</td>
<td>14</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>19,501-26,000 lbs.</td>
<td>3,679</td>
<td>33</td>
<td>39</td>
<td>0.35</td>
</tr>
<tr>
<td>7</td>
<td>26,001-33,000 lbs.</td>
<td>3,335</td>
<td>27</td>
<td>81</td>
<td>0.66</td>
</tr>
<tr>
<td>8</td>
<td>33,000 lbs. and over</td>
<td>29,849</td>
<td>32</td>
<td>1560</td>
<td>1.69</td>
</tr>
<tr>
<td>Total</td>
<td>14,001 lbs. and over</td>
<td>39,624</td>
<td>31</td>
<td>1706</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Sources: (a) U.S. Vehicles Fire Trends and Patterns; (b) TIFA; (c) VMT based on 2002 Vehicles in Use Survey [10]

As Table 2 shows, 75 percent of truck fires involve Class 8 vehicles, 29,849 Class 8 vehicles versus 39,624 total vehicles). Fatal fires are almost exclusively Class 8, with over 90 percent involving Class 8 vehicles.

Class 8 vehicles are also involved in a high rate of fire (fires per billion VMT) relative to most other weight classes. Class 6 and Class 8 trucks have the highest rates of fire per billion VMT, while Class 4 and Class 5 trucks have the lowest rates of fire. This proportion is even greater for fatal fires, where Class 8 vehicles have 2 to 5 times the rates of fire than any other weight class.

In summary, Class 8 vehicles are involved in more fire and fatal fire incidents than any other class of vehicles. They also are involved in over twice the rate of fatal fires per VMT of any other weight class. The largest and heaviest vehicles appear most vulnerable to frequent and serious fires.

**Vehicle Age**

Newer trucks encounter higher rates of fires and fatal fires per vehicle than trucks 5 years or older.
Generally, a higher incidence of fires and fatal fires exists among newer vehicles (up to 4- and 5-year-old vehicles), respectively. This trend may be due to a carrier’s higher usage, and the corresponding higher exposure of its newer vehicles. However, while the newest vehicles have the highest rate of fatal fires, they have lower rates of non-fatal fires. The effectiveness of advanced electronic safety systems on the very newest model years in this study may prevent smaller fires but may not provide timely notice of or protection from, more serious fires. The relationships between recent model year commercial trucks’ susceptibility to fires and fatal fires in particular warrant further study.

**Driver Age**

*Proportionally, younger truck drivers are more likely to be involved in fires than older drivers, whereas the opposite is true for fatal fires.*

Each point in the graph represents the proportion of total fires involving drivers in its age bracket. For example, the left-most square indicates that 4.3 percent of fatal fires involved drivers aged 18-25, the second that 8.3 percent of fatal fires involved drivers aged 26-30, etc. Accordingly, the area under each curve is 100 percent, representing all fires and fatal fires with meaningful driver age information.

Younger drivers are proportionally more likely to be involved in fire incidents than older drivers, but older drivers are more likely to be involved in fatal fires. However, no similar such dichotomy was found with crashes and fatal crashes. This finding may reflect the inexperience of younger drivers as well as older drivers’ relative physical or medical limitations. On the other hand, this may be a
byproduct of older drivers being assigned, by virtue of their experience, to the riskiest operations. The observation that younger fleet drivers are often given older equipment (less “seniority”) could also contribute to the results.

Results may also reflect age-related biases in the data source. The driver age data presented in this analysis were obtained by matching NFIRS records to corresponding FMCSA inspection records. Only records with driver age data were used in this analysis. This may over-represent certain classes of drivers. Long-haul carriers, for example, are subject to a higher proportion of FMCSA inspection, so may be over-represented in these results. If long-haul drivers tend to be younger, that could explain these results, as TIFA fatal fire records were not subject to the same matching with MCMIS.

**Likelihood of a Fire Following a Crash**

*A commercial truck fire is more than twice as likely to occur within the first 100 days following a crash than would be expected if no crash had occurred.*

The analysis team developed a hypothesis to explore whether commercial trucks are more susceptible to fire following a crash. To investigate this question, each of the 32,747 NFIRS fire records was matched by VIN and plate/state combination to MCMIS to determine if that vehicle crashed in the 1,000 days prior to the fire. This resulted in 730 matches, which were grouped by time between crash and fire in 25-day increments. These findings are displayed in Figure 3, below.

**Figure 3** Number of days since crash by fire proportion, 2003–2008.

Each diamond in the graph represents the proportion of the 730 fire-crash matches that occur within that 25-day period, with the sum total adding to 100 percent. Thus the upper left diamond represents the 5.6 percent of fires that occur within 25 days of a crash, the next represents that 4.9 percent of the fires occur from 26-50 days following a crash, etc. The solid line corresponds to a best fit for these points.

The dashed line in the graph represents the expected distribution if the fires were uncorrelated with crashes. As there are 40 data points, an even distribution of 2.5 percent of fires per period would be the expected result. Note that this result presumes that no vehicle catches fire more than once in the analysis period. As repeated vehicle fires were extremely rare in the dataset, this assumption appears quite reasonable.

As the graph demonstrates, fires occur more frequently immediately following a crash. In fact, the rate of fire occurrence is at or above the expected flat level (2.5 percent) until 200 days after the crash.
The trend-lines show an even more pronounced effect, with the solid line consistently above the flat level until 450 days after the crash. Put simply, a commercial truck fire is much more likely to occur in the period following a crash. In the first 100 days, that vehicle is more than twice as likely to be involved in a fire (and 1.5 times as likely in the first 200 days) as would be expected if no crash had occurred.

These results can be explained in a number of ways. First, vehicles in a crash can sustain un-repaired or improperly repaired damage. This damage may increase the fire risk when that vehicle resumes operation.

Second, high rates of crash and fire may both be due to another variable, such as high truck usage. Vehicles that cover high mileage, such as over-the-road trucking firms that employ team drivers, may be more susceptible to both crash and fire due to high levels of exposure. If high utilization carriers are overly represented in this dataset, this would lead to the results seen in the graph.

**Striking versus Struck**

*Commercial trucks are the striking vehicle in over 50 percent of multi-vehicle fatal fires in which they are involved.*

Vehicle fault encompasses a range of factors from unsafe driving behaviors to the basic mechanics of collisions. This portion of the analysis focuses on the striking versus struck component of vehicle fault based on whether the vehicle was labeled ‘striking’ or ‘struck’ in TIFA. Comparable data on crash roles were only available from TIFA, so it was the sole dataset used in this analysis. Table 4 compares commercial truck involvement in multi-vehicle fatal fires and multi-vehicle fatal crashes to approximate accident fault. Single vehicle accidents usually result in a unilateral determination of fault, and were thus excluded from this analysis. The vehicle role field also contains information on non-collisions and collisions; however, these data fields were excluded from this analysis because no clear distinction could be made between the striking and struck roles.

**Table 4 Commercial truck involvement in multi-vehicle fatal crashes and multi-vehicle fatal fires, 2003–2008.**

<table>
<thead>
<tr>
<th>Commercial Truck Crash Role</th>
<th>Multi-Vehicle Fatal Crashes</th>
<th>Multi-Vehicle Fatal Fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Striking</td>
<td>11,249</td>
<td>676</td>
</tr>
<tr>
<td>Struck</td>
<td>12,545</td>
<td>513</td>
</tr>
<tr>
<td>Striking %</td>
<td>47%</td>
<td>57%</td>
</tr>
</tbody>
</table>

Source: TIFA

As Table 4 demonstrates, commercial trucks are the striking vehicle in 47 percent of fatal crashes, which is 10 percent less than the proportion for fatal fires (57 percent). When vehicle role is accepted as a reasonable proxy for fault, this suggests that commercial trucks are at fault in a higher proportion of fatal fires. This discrepancy is even more apparent when compared with recent literature estimating crash fault. The *Large Truck Crash Causation Study* [8] specifically investigated crash fault from injury and fatal accidents and found truck drivers to be at fault in 28 percent of such crashes. Several State-funded studies found similar rates for crashes such as those from California (25 percent) and Florida (31 percent), as presented in FMCSA’s webinar “Large Truck Crash Misconceptions,” held in Boston, MA, April 5, 2011 [11]. These studies further support the finding that truck drivers are much more likely to be in the striking vehicle than a struck vehicle during a fatal fire.

**Correlation to Safety Regulation Compliance**

*Motor carriers with poor Vehicle Maintenance BASIC percentiles are more likely to be involved in fires.*
The Vehicle Maintenance Behavior Analysis and Safety Improvement Category (BASIC) is one of seven safety categories that FMCSA uses to group its Safety Measurement System (SMS) data, now part of the Compliance, Safety, and Accountability (CSA) program. The percentiles associated with the BASICs range from 0 to 100; the higher the percentile, the lower a motor carrier’s compliance with the Federal Motor Carrier Safety Regulations. This analysis focuses on the Vehicle Maintenance BASIC in particular because of the strong correlation found between poor performance in this BASIC and motorcoach fires in the Motorcoach Fire Safety Analysis study.

Figure 4 shows the correlation between carriers’ rate of fires and those carriers’ Vehicle Maintenance BASIC percentile.

![Figure 4](image)

**Figure 4**  Fires (per 10,000 power units) by Vehicle Maintenance BASIC percentile.
Sources: fires; NFIRS; Vehicle Maintenance BASIC percentile; SMS

As shown in the figure above, the higher a motor carrier’s percentile in the Vehicle Maintenance BASIC, the higher that carrier’s rate of fire involvement. This means that carriers that have vehicles with the most vehicle-related safety issues as identified through vehicle roadside inspections are also involved in the most fires. Carriers with the lowest levels of compliance have five times the rate of fires (25 fires per 10,000 PU) as vehicles that are the most compliant (under 5 fires per 10,000 PU).

The analysis of compliance data indicates that a carrier’s low CSA Vehicle Maintenance BASIC percentile is associated with greater fire risk for carriers and the vehicles they operate. This suggests that investigations of these carriers and inspections of their vehicles be expanded to target the discovery of fire-precursor conditions and to encourage fire preventive and mitigating practices.

**RECOMMENDATIONS FOR FURTHER RESEARCH**

The findings presented reflect the depth of research possible with available datasets. A closer look at each analysis shows the potential for data improvements. These data could take the form of a more complete census of CMV fires and/or additional granularity and precision in record detail. These details will in turn provide a more complete picture and less potential for bias, respectively.

Stronger vehicle identification data would significantly improve the data refinement process, for one. Many NFIRS fire records could not be identified as CMV, and were therefore preemptively excluded.

Additionally, many of the results in this paper reflect underlying differences in driver or carrier behavior, a topic out of scope for this paper. For example, in the case of fire rates by vehicle age or driver age, owners of newer vehicles and/or younger drivers may drive a different distribution of routes. Data on the relationship between these variables and carrier business model, number of hours driven per day, and similar variables could all further explain these differences.
Correlation of fires to future crash could also have a behavioral link that could be further explored with more detailed behavior-level data. Business model and driving patterns may identify classes of drivers who are at higher risk of both crash and fire due to high on-road exposure (e.g., the high hours of team driving operations). These hypotheses all deserve further exploration with more granular behavioral data.

The ‘striking/struck’ analysis could also be significantly improved. This could involve partnering with large carriers to harness their own more extensive datasets, focusing research more on the frequency / likelihood of reporting for parked vehicle fires and crashes. Also, directly accessing data from police accident reports will provide a direct measure of ‘fault.’

Finally, the fire rates presented in this paper could also be significantly refined with stronger normalization data. The reason for using exposure data is to accurately reflect true on-road risk. Higher quality VMT or vehicles-in-operation information, especially captured on an individual -truck basis, would provide a more solid grounding for determining the fire rates. Taken together, these examples point to data improvement as an essential step towards understanding, preventing, and mitigating the consequences of future CMV fires.

REFERENCE LIST

Methodology of fire growth and toxic gases production simulation - Application to an european train vehicle

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ABSTRACT

This paper deals with the fire safety methodology applied in european railway transport, during a project called Transfeu. The objective of this methodology is to simulate the fire growth and the toxic gases dispersion in a train vehicle in order to estimate life expectancy for a given design fire scenario. In first time, three different methods are used to simulate the pyrolysis and the fire behaviour of polymer materials. In second time, two approaches are used to predict the released toxic gases. The methodology adopted is a multi-scale approach, from the matter to the real scale, whose the aim is to verify the model capability to reproduce various fire scenario in train vehicle. The methodology is illustrated through some examples. Advantages and limits of each approach are explained.

KEYWORDS: fire safety methodology, multi-scale, fire behaviour, toxic gases, FDS.

INTRODUCTION AND CONTEXT

Nowadays in Europe, products present inside train vehicle are low spread of flame characteristics. This performance comes from the regulatory safety requirement set up by each European country [1]. An European fire safety railway standard [2] is going to apply soon in order to harmonize the requirements for the railway transport network in Europe. This standard takes into account the fire resistance and fire reaction characteristics of the different products, depending on their usage, the operation category and the type of train vehicle [3].

When a luggage fire happens in a train, the products into the vehicle may take several minutes to participate to the fire growth. Even if the materials of the vehicle do not burn during the first minutes, it can start to decompose and to form toxic gases. A train vehicle is a quasi-closed system, where a high density of passengers could be exposed to these toxic gases before their evacuation through the platform or in safer places in the train itself.

The European research project “Transfeu” (Transport Fire Safety Engineering in the European Union) studies the fire behaviour and the formation of toxic gases of train products [4]. One of Transfeu’s major objectives is to predict the impact of fire during passengers evacuation. In the future, these research results could be extended to other surface transportation, like ships and buses. This present paper focuses on the fire safety engineering methodology, applied in Transfeu to predict the reaction-to-fire of several train products. It presents the methodology used to predict toxic gases generation and their transport in order to determine an incapacitation time during people evacuation into the train. The approach is based on the use on the computational fluid dynamic code, Fire Dynamic Simulator (FDS) Version 5.5 [6].

It is important to predict correctly the heat release and the mass loss before the prediction of the toxic gases generation. In the first part, different kinds of methods used to model the pyrolysis of polymer materials and the fire growth are presented. In the second part, two methods to predict the toxic gases release rate in FDS are described. Finally, first results of the comparison between experimental tests and FDS simulation are analysed.
MULTI-SCALE APPROACH

The methodology used in Transfeu project is based on a multi-scale approach. It comprises three phases: experiments on tests rigs of increasing scale, numerical simulation of these experiments and comparisons and feedback corrective action regarding input parameters used for simulation if necessary. This comparison at increasing complexity allows to observe the ability of the model to reproduce realistic simulations (figure1).

![Figure 1: Multi-scale experimental and numerical approach](image)

In our study, analysis are performed at six different scales (figure 1):

1. **The matter scale**: The experimental test is carried out from a Thermogravimetric Analysis (TGA) coupled with the Differential Scanning Calorimeter (DSC). The principle is to measure the reactivity of few milligrams of material in function of the heating rate temperature to understand the thermal and oxidative decomposition of the material. The analysis allows to define a reactional mechanism for the tested material. The modelling of these thermal decomposition process implies to estimate kinetic parameters, necessary for pyrolysis modelling with FDS.

2. **The material scale**: Two tests are performed at material scale:
   - The Smoke Box (SB) [7] test coupled with Fourier Transformed Infrared (FTIR) spectrometer in a prescriptive way. Few hundred grams are needed for these two tests. The aim of the SB test [7] is to determine the smoke opacity and the quantity of each type of gases released (function of the FTIR calibration).
   - The Cone Calorimeter (CC) test [8] coupled with Fourier Transformed Infrared (FTIR) spectrometer. The objective is to understand the reaction-to-fire of the material via the heat released rate, the mass loss rate measurements of samples of 100*100*thickness mm³ at different heat fluxes and the quantity of each type of gases released.

   The aim of this scale analysis is to perform the ability of FDS to predict the reaction to fire of materials and the interaction between layers for instance.

3. **The semi-finished scale**: The Medium Burning Item (MBI) [9] test allows to study the fire behaviour and the fire spread only on a vertical products. The MBI simulation objective is to validate the ability of the FDS code to predict the fire spread and to confirm the material properties.

4. **The product scale**: The fourth scale follows the Open calorimetry test [10] and represents the product in real condition, i.e. the configuration, the dimension and the structural geometry of the product. The heat source is a propane burner, like for the fifth and the sixth scales while the previous scales use a radiant source. This product scale simulation verifies the effect of the test configuration (impact of the ceiling and the corner) on the fire growth (fire reaction and fire spread) of the material.
5. **The compartment scale**: This scale is performed to understand and compared with FDS simulation the effect of the closed compartment on the fire growth of several products and their toxic gases formation. The propane burner used for this scale is the same than those of the product scale.

6. **The real scale**: This experiment test is realised in a real train vehicle. The design fire scenario was selected by the Transfeu consortium according to a fire risk analysis [3]. All materials used are the same as the compartment scale. The aim of this real scale is to verify the fire growth and the quantity of toxic gases released in FDS simulation with the real fire scenario condition test (vehicle configuration). Then, the final objective of the real scale FDS simulation is to assess the toxicity impact on the passengers during the evacuation.

In FDS, the behaviour in solid phase (such as material) is processed separately from the gas phase. Indeed, the fire growth process and the toxic gases formation are driven respectively by the solid phase and by the gas phase. For this reason, the methodology presented in the next section is divided in two parts, one focuses on the fire behaviour of materials while the other one presents the kinetic of released gases.

**DESCRIPTION OF THE METHODOLOGY TO SIMULATE THE FIRE GROWTH PROCESS**

The multi-scale methodology was proposed and adopted by several authors [5,11] to evaluate the ability of CFD code to predict the fire growth. Following this principle, Transfeu working group relies on several modeling approach: the prescribed source, the controlled prescribed source and the calculated pyrolysis. Those approaches are possible with increasing complexity according to FDS model limits. Each of them is studied with a multi-scale modeling approach, as shown on figure 1. The major difference between the prescribed source method and the two others is that in this method the fire spread is entirely prescribed by the FDS user while, concerning the two others, the fire spread is simulated according to FDS models. The next important difference between the calculated pyrolysis method and the two others is that the fire reaction is driven by the FDS pyrolysis model. Whereas, in the prescribed source method and in the controlled prescribed source method the fire reaction kinetic is prescribed by the FDS user.

**The ‘prescribed source’ method**

The prescribed source method is the most simple method applied in FDS. It does not require a lot of input data. Furthermore, the mesh size of the product in FDS has not an influence on the fire behaviour because the fire spread is not modelled by FDS but totally prescribed by the FDS user. The multi-scale approach of this method starts from the material scale (CC test [8]) up to the real scale (figure 2).
The first step is the definition of the required input data in order to calculate the temperature, density, velocity and pressure of the gas phase in FDS at the product scale, as shown in Figure 2:

- the heat release rate per square meter (HRRPUA): This vector data is obtained from the cone calorimeter test [8]. The test conditions, particularly the irradiance of the cone heater, are defined on the EN45545 [2]. Additional tests can be performed from 15 to 75 kW/m².
- the burnt area from product scale test.
- the boundary conditions (initial temperature, pressure, ventilation, back product condition).
- the material properties (chemical composition and effective heat of combustion).

Then, the next step is to compare output data from FDS product simulation with experimental measurements of the product scale test. The comparison between the experiments results and the FDS simulation is performed on the heat released rate, the product mass loss rate, the atmospheric pressure and the surface product temperature. When the models of the code reproduce the fire behaviour of all types of products, these FDS input data are tested at the higher scales: the compartment scale and the real scale.

The drawback of this method is that all input data are prescribed by the FDS user and come from different scales, i.e. the fire spread is not modelled. Moreover, input data are highly dependent on the fire conditions. The advantage of this method is that its simplicity due to the small quantity of input data needed for FDS and the calculation time period is short (few hours).

The ‘controlled prescribed source’ method

In this method, the fire reaction is prescribed by the FDS user from experimental test, while the fire spread is driven by the FDS thermal models. The multi-scale approach starts from the material scale up to the real scale (Figure 3).
As the previous method, the HRRPUA vector, the boundary conditions and the materials properties need to be specified (figure 3). New properties are required: the ignition temperature of the surface of the product, the density, the thermal conductivity, the heat capacity and the emissivity of each material [12]. These properties are estimated from the CC tests [8] or the literature. They are then validated with a cone calorimeter FDS simulation. The objective of this simulation is to find the same ignition time at cone calorimeter scale in FDS and in experiment. Concerning vertical product, the FDS input data (the ignition temperature) is adjusted, if necessary, and then confirmed at semi-finished scale. In this study, the ignition temperature is not a physical or a real parameter but a numerical parameter adapted to the FDS thermal models.

The next step is to confirm FDS material properties from FDS material properties at semi-finished and product scale. When this verification is obtained for all types of products, then these FDS input data are tested at higher scales: the compartment scale and the real scale.

The drawback of this method is that the FDS mesh size has an important influence on the fire spread at higher scale [5]. As the previous method, the input data are highly dependent on the fire conditions. An other drawback is that when several types of fuels are present in FDS simulation, the oxidised fuels release the same quantity of energy, because only one type of fuel exists in FDS (via the only one combustion reaction). The advantage of this method is that FDS input data come only from the small scales (material and semi-finished scales) to predict the fire behaviour at higher scale (product to real scales).

The ‘calculated pyrolysis’ method

The interest of this method is to predict accurately from FDS models the pyrolysis and the fire behaviour of products at real scale test. The multi-scale approach starts from the matter scale up to the real scale (figure 4).
The aim of the matter scale is to estimate kinetic parameters required for FDS material scale simulation (figure 4). Kinetic parameters of each reaction of the material thermal decomposition are essential to calculate the FDS pyrolysis model and then to predict the mass flow of the fuel in FDS [5,11,14,15]. Thus, kinetic parameters are assessed by an optimized modelling approach at matter scale (figure 4) for each material of each product [5,11,13-16]. Furthermore, thermal properties are assessed for each reaction of each material by literature and with DSC tests [16]. The effective heat of combustion of each reaction is estimated by the CC test. When all parameters are estimated, the next step is to compare experimental data from cone calorimeter test [8] with numerical output data of the cone calorimeter simulation in FDS in order to verify material properties estimated at matter scale (figure 4). Compared data are the ignition time, the material mass loss rate and the heat released rate. At the end of this step, material properties of each material are confirmed. The following step in figure 4 is to verify the ability to FDS to predict the fire growth at the product, the compartment and the real scales with the material properties of the material scale. Compared data are: heat released rate, mass loss rate, surface product temperature, burnt area and ignition time.

The major drawback of this method is that it requires a lot of input data, which are difficult to assess and need an optimization modelling program [11]. Moreover, this method requires a particularly thin mesh size to represent accurately the fire growth. However, advantages of this method is when real scale simulation is validated from the matter scale, thus, an other configurations of the design fire scenario are conceivable with the same products.

**DESCRIPTION OF THE METHODOLOGY TO SIMULATE THE KINETIC OF RELEASED GASES**

**Toxic gases generality**

Firstly, there are two categories of toxic gases: narcotics (CO, HCN, CO₂) and irritant gases (HCl, HF, HBr, NO₂, SO₂, Aldehyde). Narcotics gases cause a decrease in oxygen supply to body tissue, resulting in central nervous system depression, with the loss of consciousness and ultimately death [17]. Irritants gases cause immediate incapacitation, mainly by effects on the eyes and upper respiratory tract and longer-term damage deeper in the lung [17]. The standard ISO 13571 [18] introduces two toxicity models: the fractional effective dose (FED) for narcotics and the fractional effective concentration (FEC) for irritants gases, in order to estimate the effect of toxic gases on people. These models take into account the gases concentrations inhaled at this instant $t$ by people for FEC and the narcotics dose accumulated during a time period for the FED model.

Toxicity is not a material characteristic [19]. Each formation kinetic of each toxic gases depends on the material composition and the fire conditions (oxygen concentration and ventilation). Toxic gases source can provide from [20]:

- the pyrolysis of the material,
- the combustion of the material and slightly affected by flame,
- the combustion of the material and strongly affected by flame,
- the char oxidation.
Toxic and combustible gases can be modelled in FDS according to two methods, the first one is implemented in FDS and the second one is an alternative approach proposed. Toxic gases and the fuel are formed and dispersed in the domain with Navier-Stokes equations and equation of state [6] (figure 5). According to the evacuation scenario and an output data processing, FDS user can estimate toxicity and then a life expectancy for this given scenario, (figure 5).

First method: Generation of toxic gases implemented in FDS
In FDS, the gases source is provided only from the combustion reaction and is based on several hypotheses [6]:

- The combustion is based on a mixture fraction $Z$ model. At any time and in each mesh, $Z$ gives the mass fraction corresponding to the species present in the combustion equation (Eq.1).
- Global and only one combustion equation (only one fuel gas can burn even if several combustibles are present)
- Combustion is supposed infinitely rapid. The fuel species and $O_2$ from air can not be present at the same time in the same mesh. Diffusion phenomenon in flame are not represented.

Either the mesh is flaming or not.

The following equation is the global combustion equation used in FDS:

$$C_3H_yO_zN_xOther_{w} + v_{O_2}O_2 \rightarrow v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_{SOOT}Soot + v_{H_2}H_2 + v_{N_2}N_2 + v_{Other}Other$$

Eq. 1

Following eq.1, the fuel is composed of 5 compounds maximum, which are carbon, hydrogen, oxygen, nitrogen and one other compound that FDS user may define. Combustion products in gas phase are carbon dioxide, water, carbon monoxide, soot, hydrogen, nitrogen and the same other compound (that FDS user choose in reactant product). Furthermore, a two-steps combustion equation exists in FDS, corresponding to the carbon monoxide oxidation in flame, as eq.2.

$$C_3H_yO_zN_xOther_{w} + v_{CO}CO \rightarrow v_{CO_2}CO_2 + v_{SOOT}Soot + v_{N_2}N_2 + v_{Other}Other$$

$$v_{CO}C + \frac{1}{2}O_2 \rightarrow CO_2$$

Eq. 2

Concerning the one step or the two steps reactions, the toxic gases (CO and CO$_2$) mass fraction is modelled in FDS from the fuel mass fraction and the mixture fraction $Z$. Their kinetics of formation depend on the mass flow and the oxygen yield in the domain. However, there are not only CO and CO$_2$, as toxic gases, from the combustion of Transfeu materials. Thus the second method,
explained in the following part, how all toxic gases released from a material combustion are taken into account.

**Second method: Toxic gases released in FDS with track species (new approach)**

The aim of this second complementary method is to take into account:

- Several other toxic gases than CO and CO₂, such as: HCN, NOₓ, HCl, HBr, HF and SO₂
- The potential toxicity of several materials.

The principle of this method it to predict kinetic released gases yield during the different stages of fire at each time of the test [21]. One track species is released during one stage fire. Each track species is composed of several toxic gases compound as defined on figure 7, with one affected transport equation. The kinetic of the released gases does not depend of the FDS combustion equation and the mixture fraction model but it depends on the CC [8] + FTIR tests (figure 5). Moreover, several strategies of evacuation in the train for people are studied. Finally, the toxicity is assessed according to performance and acceptance criteria, required by Transfeu working group, such as FED = 1 (one half of the population are incapable of effecting their own escape [18]) or FED = 0.3 (11.4 % of the population are incapable of effecting their own escape [18]). According to these criteria, a life expectancy is estimated (figure 5).

To begin, it is very important to describe precisely the fire scenario, such as the fire source, the materials supposed to burn and the atmospheric and ventilation conditions, because FDS user is going to do some hypothesis from this description. Then, when all these points are known, it is possible to define the fire stages. Several fire stages are described in the standard ISO 19706 [22]. Three major fire stages exist, non flaming, well-ventilated flaming and under-ventilated flaming. The following curve (figure 6) describes an example of the heat release rate versus time of a fire scenario. Three different products are considered in this scenario, the burner, the seat and the panel. In this example, the fire scenario follows three steps during its development of different products, such as:

- Pyrolysis of the seat and fire well-ventilated of the propane burner (1st stage)
- Fire well-ventilated of the propane burner and the seat materials (2nd stage)
- Fire well-ventilated of the propane burner, the seat and the panel (3rd stage)

Furthermore, when the fire growth is validated with experiments tests, the third step of this method is to use the kinetic yield toxic gases data from the CC [8] + FTIR test. The main hypothesis is to assume that the cone calorimeter test represents the same fire conditions as in real tests (product and real scale test). The goal is to use data from a small scale tests to a product scale tests. The cone calorimeter test [8] has been chosen among the small scale test because two different fire stages are present in this test: the non flaming and the well-ventilated flaming stages. A FTIR spectrometer is coupled to the CC test [8] to quantify the toxic gases (CO, CO₂, HBr, HCl, HCN, HF, NOₓ, SO₂). Then, the kinetic of mass loss rate and the heat release rate of the cone calorimeter test [8] are compared with the kinetic of released toxic gases. The aim of this comparison is to determine for each material:
• Which toxic gases are released during the CC test [8] and their yield?
• What are their production time periods?

After, released toxic gases from each fire stage is named track species as presented on figure 7. A track species is composed of several toxic gases of one fire stage.

Figure 7: Production of each tracer species function of each fire stage

These three tracer species can be represented with a matrix, as table 1 [22]. The model concerns only one material M for instance. Each track species is composed of eight toxic gases species in this example according to ISO 13571 [18].

Table 1: Production matrix of material M with 8 toxic gases and 3 fire stages

<table>
<thead>
<tr>
<th>Material M</th>
<th>Track species 1 (1st fire stage)</th>
<th>Track species 2 (the 2nd fire stage)</th>
<th>Track species 3 (the 3rd fire stage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>CO2TS1</td>
<td>CO2TC2</td>
<td>CO2TC3</td>
</tr>
<tr>
<td>CO</td>
<td>CO TS1</td>
<td>CO TC2</td>
<td>CO TC3</td>
</tr>
<tr>
<td>HCN</td>
<td>HCN TS1</td>
<td>HCN TC2</td>
<td>HCN TC3</td>
</tr>
<tr>
<td>HCl</td>
<td>HCl TS1</td>
<td>HCl TC2</td>
<td>HCl TC3</td>
</tr>
<tr>
<td>HBr</td>
<td>HBr TS1</td>
<td>HBr TC2</td>
<td>HBr TC3</td>
</tr>
<tr>
<td>HF</td>
<td>HF TS1</td>
<td>HF TC2</td>
<td>HF TC3</td>
</tr>
<tr>
<td>NO2</td>
<td>NO2 TS1</td>
<td>NO2 TC2</td>
<td>NO2 TC3</td>
</tr>
<tr>
<td>SO2</td>
<td>SO2 TS1</td>
<td>SO2 TC2</td>
<td>SO2 TC3</td>
</tr>
</tbody>
</table>

During the product and real scales tests, several materials are present. Thus, it is important to build a matrix for a system, such as a train vehicle, which holds n materials. This new matrix, described in Eq 3, depends of the scenario, such as:
• The number of materials which are likely to burn (from 1 to n materials).
• The number of fire stages (here three fire stages).
• The type of material which participates to the fire stage.
• The mass proportion of the material i in the system.

$$[	ext{ M}_i] = \sum_{i=1}^{n} P_{(i, \text{Stage}1)} \cdot [\text{ M}_i] + \sum_{i=1}^{n} P_{(i, \text{Stage}2)} \cdot [\text{ M}_i] + \sum_{i=1}^{n} P_{(i, \text{Stage}3)} \cdot [\text{ M}_i]$$  \hspace{1cm} \text{Eq. 3}$$

Where:
[\text{System}]$\;\text{Global matrix of released toxic gases for all the system}\)

$P_{(i,\text{Stage1})}$: Proportion of the material $i$ in the system during the first fire stage

$P_{(i,\text{Stage2})}$: Proportion of the material $i$ in the system during the first fire stage

$P_{(i,\text{Stage3})}$: Proportion of the material $i$ in the system during the first fire stage

$[\text{System}]_M$: Matrix of released toxic gases of the material $i$ for each fire stage (table 1)

When the FDS user has estimated the global matrix of released toxic gases for all system ($[\text{System}]$) with FITR analyser and based on hypothesis (as proportion of material which are involved of each fire stages in each track species), the calculation of the FED/FEC model at each time period and space of the simulation is estimated with sensors placed in FDS simulation.

**EXAMPLE OF APPLICATIONS IN TRANSFEU PROJECT**

In this section, research is still ongoing and active. Results of the methods 1, 2 and 3 to predict the fire growth until the product scale of one material are presented. The studied material is a glass reinforced polymer composite used as an inside vertical panel of a train vehicle. The FDS simulation results are presented from the material to the product scale and only on the heat released rate measurement.

**Material scale (input data concerning the method 2)**

Figure 8 shows the experimental results of the CC tests of the laminate composite material at three different irradiance levels (35, 50 and 75 kW/m²). Concerning the method 2 (the ‘controlled pyrolysis method’), the ignition temperature has been estimated at $370^\circ \text{C}$ for a mesh size of $2.5 \text{ cm}$ and for the three irradiance levels. The vector of heat release rate (at an irradiance level of $50 \text{ kW/m}^2$), and this ignition temperature are a part of the input data set for the method 2.

**Semi-finished scale**

The figure 9 and 10 give the comparison of experimental and FDS simulation of the composite material of the MBI test at $50 \text{ kW/m}^2$ (irradiance level) respectively at $2.5 \text{ cm}$ and $1 \text{ cm}$ (mesh size). Firstly, the ignition temperature in FDS was taken as the same as the material scale, such as $\text{Tig} = 370^\circ \text{C}$. In figure 9 and 10, for the two different mesh sizes, the quantity of the simulated heat release (for $\text{Tig} = 370^\circ \text{C}$) is higher than for the two experimental tests. Consequently, a new numerical ignition temperature is adjusted as the quantity of heat release is the approximately the same as the experimental ones. This new numerical ignition temperature is $470^\circ \text{C}$ for all mesh size. This numerical temperature will then be confirmed for the product scale comparison. However, data analysis on this scale is still ongoing.

![Figure 8: Heat released rate of three CC tests of the composite material – Input data used in the Method 2](image-url)
Product scale
The panel is heating by a propan burner (75 kW during 2 min and 150 kW during 8 min). The figure 11 presents the comparison between experimental test and the FDS product scale simulation at three different size meshes (2.5, 5 and 10 cm). Input data of FDS simulation of the figure 11 are the same that the one of the semi-finished scale (Tig = 470°C). The experimental and numerical ignition time are quite similar (figure 11 and 12). Furthermore, concerning this scale and the method 2, more the mesh size is wide, more the heat release has the same kinetic than the experimental tests. The figure 12 is the comparison between the methods 1, 2, 3 and FDS simulations at 2.5 cm (mesh size) and the two tests. Hypothesis (ignition time and burnt area) used to simulate the method 1 are correct concerning the heat release rate measurement because the method 1 simulation have the same trend than the product tests. The heat released rate from the method 3 has approximately the same kinetic and a higher intensity than the two experimental tests.
CONCLUSION

The objective of the present work is the development of the multi scale approach applied in Transfeu project in order to simulate the fire behaviour and the toxic gases emissions and dispersion. Two different methodologies (with different methods for each one) are presented, one for the fire growth and an other one for the toxic gases generation, in the code FDS version 5.5. Their principle is to verify the ability of the FDS code to reproduce scale by scale the fire behaviour and the toxic gases generation with the comparison of experimental tests.

Concerning the fire growth methodology, the calculated pyrolysis method requires a lot of FDS input data than the controlled prescribed source and the prescribed source methods. Some of these input values are difficult to assess and must correspond to the FDS physical models, such as kinetic parameters. However, the advantage of this method is that the pyrolysis is accurately defined and their input data in FDS do not depend on the fire conditions.

The two methods of the released toxic gases methodology depend on the FDS models. The first one uses the combustion reaction implemented in FDS. The second one tries to complete the first one with additional passive released toxic gases effluents. This method allows to identify and to estimate the mass yield of eight gases according to the fire stages of the scenario. An other important point is that...
this method allows to take into account several toxic gases from several fuels. Only one transport equation is used for each track toxic gases species, thus calculation time is not too long and depends of the meshes size. Limitations of this method are that the released toxic gases effluents depends of the same fire conditions of the cone calorimeter test and there is no interaction, i.e. possible reaction or recombination, between each toxic gas in FDS. The first results of the fire growth methodology are encouraging and complementary results will be published in a future paper.

Acknowledgments
The authors would like to thanks all the Transfeu partners. The authors aknowledge the financial support given by the European Commission.

References:
[13] G. Rein, Computational model of forward and opposed smoldering combustion with improved chemical kinetics, University of California, Berkeley, 2005
[22] ISO 19706, Guidelines for assessing the life threat to people, 2011
Fire safety performance of buses

Anja Hofmann & Steffen Dülsen
BAM Federal Institute for Materials Research and Testing, Berlin, Germany

ABSTRACT
The amount of plastic materials used in all sectors of everyday life is still growing. The plastic materials also have gained to a major importance in the automotive industry. Today they are widely used in vehicles because of their excellent mechanical properties and their light weight combined with cheap production costs. But unfortunately these materials appear to be ideally suited to endanger passengers in case of fire. Bus fires occur relatively frequently, however in most of the cases without personal damage. Almost every day (350 - 400 bus fires per year [1]) a bus burns in Germany which conforms to circa 0.05 % of 76,433 busses registered in Germany [2]. An internal investigation of a big German bus operator also found out that every year 1 % of all busses had fire incidents. In 2008 a severe bus fire occurred in Germany where 20 of 32 passengers lost their life. Since smoke and its toxicity play an essential role in bus fires a research project covering these topics funded by the German Federal Highway Research Institute (BASt) has been started at BAM. That severe bus fires still occur in Germany is shown by bus fires in May 2011 [3] or in February 2012 [4] where fortunately young and fit passengers (pupils) could escape early enough through windows which they had to destroy. The luck and fitness of these pupils prevented further losses of lives in both bus fire cases.

In the bus fire project small, intermediate and large scale experiments on material specimen, interior parts and vehicles have been performed, as well as numerical investigations. The investigations, results and recommendations developed by BAM within this project are presented here.

KEYWORDS
Large scale fire tests, numerical simulation, bus interior materials, smoke toxicity, recommendations

DIRECTIVES AND TEST METHODS FOR BUSSES IN GERMANY AND EUROPE

In Germany the safety of road vehicles is basically regulated by the German Road Traffic Licensing Regulation (StVZO) in which also the legal requirements of European directives are implemented. Generally the §30 StVZO demands a vehicle construction and equipment for a maximal passenger safety, especially in case of a traffic accident. The §30d StVZO specifies the requirements for busses and is complemented by the appendixes I to VI, VIII, IX of the EU directive 2001/85/EC (called ‘bus directive’). Regarding the fire safety of busses the §35g StVZO demands fire extinguishers, the §45 StVZO defines the requirements for fuel tanks and the §46 StVZO regulates the requirements for fuel lines. Concerning the reaction to fire of bus interior materials the §35j StVZO rules the requirements which are complemented by the appendixes IV to VI of the EU directive 95/28/EC. The fire safety requirements of bus interior materials are not mandatory for city buses, because ‘this directive applies to the burning behavior (ignitability, burning rate and melting behavior) of interior materials used in vehicles of category M3 carrying more than 22 passengers, not being designed for standing passengers and urban use (city buses)’ [scope extract of 95/28/EC].

EU directives often correspond to regulations of the UN-ECE (the United Nations and the Economic Commission for Europe) which harmonize international economic standards under the administrative direction of the United Nations headquarters. The ECE R 36 regulate the ‘uniform provisions concerning the approval of larger passenger vehicles with regard to their general construction’. The ECE R 107 contains the ‘uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction’ which mirror the directive 2001/85/EC. The ECE R 118 is similar to the 95/28/EC and regulates the ‘uniform technical prescriptions concerning the burning behavior and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles’. In Table 1 the existing fire safety requirements for busses in Germany
The actual effective fire tests were derived from the American FMVSS 302 standard which was developed in the nineteen sixties. Since then plastic materials have gained a major importance in the automotive industry. But the flammability and burning behavior of plastic materials has not yet been taken into account in the requirements. In a modern bus the fire load of plastic parts installed in the passenger compartment exceeds for example the fire load of the filled diesel tanks. But in difference to bus interior materials the fuel tanks are well shielded against fire. The prescribed fire tests for interior materials only consider small ignition sources like cigarettes or lighters although bus fires are mostly the results of defects in the engine compartment, crashes or defects in electronics. The fundamental reaction-to-fire test for bus interior materials is a test procedure to investigate the horizontal burning rate of a small flame on a rectangular specimen. The burning rate between two defined marks is monitored. If the flame does not reach the second mark the burning distance has to be measured. The bus interior material passes the flammability test if the worst result does not exceed a horizontal burning rate of 100 mm/min. Ceiling materials and bordered parts have to pass an additional drip test regarding their melting behavior. Also a cotton ball is placed on the bottom below the specimen. An electrical heater (Epiradiateur) radiates a thermal intensity of 30 kW/m² to the specimen. During the test period the drip and ignition behavior of the specimen and the underlying cotton ball are monitored for ten minutes. The requirements are fulfilled if there is no dripping during the test which ignites the cotton ball. In the test procedure four specimens have to be tested in their practice-oriented direction. Drapes, jalousies and hangings also have to pass an additional test which investigates the vertical burning rate. In this process three specimens have to be tested in their practice-oriented direction. If the material is anisotropic, it must be six specimens. The requirements of the test are passed if the worst vertical burning rate is lower than 100 mm/min.

The fire safety directives for bus interior materials in Germany and the EU are similar to all fire safety requirements for interior materials used in road vehicles around the world. In Table 2 national and international directives and manufacturer’s specifications are summarized.
Test procedure of 95/28/EC (and ECE R 118)

<table>
<thead>
<tr>
<th>Test procedure</th>
<th>Standards</th>
<th>Manufacture’s specification</th>
</tr>
</thead>
</table>
| Appendix IV  (Appendix VI) | Test to determine the horizontal burning rate of materials | ISO 3795 (Int.)  
FMVSS 302 (USA)  
U.T.A.C. 18-502/1 (F)  
DIN 75200 (D)  
BS AU 169 (GB)  
JIS D 1201 (J) | GS 97038 (BMW)  
DBL 5307 (Daimler)  
FLTM-BN 24-2 (Ford)  
GM 6090 M (GM)  
MES DF 050D (Mazda)  
ES–X60410 (Mitsubishi)  
PTL 8501 (Porsche)  
D45 1333; (Renault)  
STD 5031,1 (Volvo)  
TL 1010 (VW) |
| Appendix V (Appendix VII) | Test to determine the melting behavior of materials | NF P92-505 (F)  
U.T.A.C. 18-502/2 (F) | |
| Appendix VI (Appendix VIII) | Test to determine the vertical burning rate of materials | EN-ISO 6941 (Int.) | |

Table 2 – Test procedure of 95/28/EC and ECE R 118

Regarding the fire safety performance of busses Germany together with other contracting parties is and was to enhance the UN/ECE-regulations for bus fire safety. In Table 3 the results achieved and next steps being under discussion, preparation or being research items are shown.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Directive</th>
<th>Status</th>
<th>Obligation as from (new approval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire / smoke detectors in enclosed spaces</td>
<td>ECE-R 107</td>
<td>discussion finalized</td>
<td>2014 / 2015</td>
</tr>
<tr>
<td>Reaction-to-fire, interior materials (burning velocity, vertical test for vertical mounted materials)</td>
<td>ECE-R 118</td>
<td>discussion finalized</td>
<td>middle 2016/ middle 2017</td>
</tr>
<tr>
<td>Suppression systems: engine area</td>
<td>ECE-R 107</td>
<td>in preparation (international)</td>
<td></td>
</tr>
<tr>
<td>Toxicity and smoke development</td>
<td>research project</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency exits</td>
<td>ECE-R 107</td>
<td>under discussion (GRSG)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 – Recent requirements on UN/ECE-level

TEST METHODS OF OTHER PASSENGER TRANSPORT SECTORS

Regarding the assessment of the fire safety performance of busses an overview about the fire safety regulations in other passenger transport sectors is necessary. Table 4 shows a comparison of fire safety requirements and tests for interior materials in different transport sectors.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Road vehicles</th>
<th>Rail vehicles</th>
<th>Shipping</th>
<th>Aviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire safety directives</td>
<td>95/28/EC, ECE R118</td>
<td>96/48/EC, DIN 5510</td>
<td>SOLAS Chapter 11-2</td>
<td>FAR 25</td>
</tr>
<tr>
<td>Bunsen burner tests</td>
<td>ISO 3795</td>
<td>ISO 5658-2</td>
<td>Subpart 164.012</td>
<td>FAR 25.853/855</td>
</tr>
<tr>
<td>Tests with a Cone Calorimeter</td>
<td>ISO 5660-1</td>
<td>ISO 5660-1</td>
<td>Subpart 164.012</td>
<td>FAR 25.853</td>
</tr>
<tr>
<td>Tests in a Smoke Density Chamber</td>
<td>ISO 5659-2</td>
<td>ISO 5659-2</td>
<td>FAR 25.853</td>
<td></td>
</tr>
<tr>
<td>Radiation tests (e.g. for the floor)</td>
<td>EN-ISO 9239-1</td>
<td>Subpart 687.017</td>
<td>FAR 25.856</td>
<td></td>
</tr>
<tr>
<td>Seat tests</td>
<td>DIN-EN 45545-2</td>
<td>A.563 (14)</td>
<td>FAR 25 Part II App. F</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Overview of fire safety requirements in different transport sectors

This comparison shows that most of the reaction-to-fire tests which are required in other transport sectors...
sectors are not mandatory for road vehicles. The heat release rates for example which can be determined with a Cone Calorimeter (ISO 5660-1) is not considered. Investigations for smoke production, smoke gas concentrations and toxicities which can be detected for instance with an FTIR (Fourier Transmission Infrared Spectroscopy) coupled with the Smoke Density Chamber (CEN/TS 45545-2/ ISO 5659-2) or other smoke tests are also disregarded. Tests for the effect of heat radiation are only required for few bus interior parts and only with a low irradiance level. Extra fire safety requirements for bus seats (e.g. against arson) do not exist. Generally interior materials for road vehicles have to comply with the lowest fire safety requirements in comparison to all other passenger transport sectors. The highest requirements are demanded to airplanes because the escape during the flight is not possible and the kerosene contains a high fire risk, as well. Also the escape on sea is hard to realize. Therefore the fire safety requirements for passenger ships can be ranked between the requirements for airplanes and transportation systems on land. But in difference to ships and airplanes the escape conditions for passengers in road and rail vehicles are quite easier. Only tunnels and bridges constitute higher risks in case of fire which has to be extra considered. But this is not implemented in requirements for bus interior materials despite that bus fires occur relatively frequently. The fire safety performance of interior materials for rail vehicles is clearly higher than for road vehicles. Especially regarding their heat release rates and their smoke gas toxicity the interior materials of road vehicles are not restricted though the operation conditions are quite similar. Therefore requirements for bus interior materials should be absolutely enhanced. ([5], [6])

The fire safety performance for bus interior materials could be inspired by regulation for trains. The operating conditions of busses are comparable with these of rail vehicles, e.g. city buses and trams in cities or tour coaches and long-distance trains on open country routes with long tunnels and bridges. The directive for rail vehicles already differs in the objective from the principles of road vehicles. The DIN 5510 [7] and newer CEN/TS 45545 [8] demand requirements against the possibility of arson and against the ignition as a consequence of a technical defect as well as the declaration of unavoidable fires. The CEN/TS 45545-2 regulates the fire safety requirements of materials used in rail vehicles including their test methods, parameters and valid thresholds. A requirement class specifies the test methods including the parameters and the thresholds in accordance to the corresponding Hazard Level (HL) of a material by classifying the end-use application. A Hazard Level depends on the severity of the restriction by evaluating the operation conditions (see Table 5) and the construction form (see Table 6).

<table>
<thead>
<tr>
<th>Operation category</th>
<th>Service</th>
<th>Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mainline, regional, urban and suburban</td>
<td>Operation not determined by underground sections, tunnels and/or elevated structures</td>
</tr>
<tr>
<td>2</td>
<td>Urban and suburban</td>
<td>Operation determined by underground sections, tunnels and/or elevated structures with walkways or other means for safe side evacuation from the vehicles</td>
</tr>
<tr>
<td>3</td>
<td>Mainline and regional</td>
<td>Operation determined by underground sections, tunnels and/or elevated structures with walkways or other means for safe side evacuation from the vehicles.</td>
</tr>
<tr>
<td>4</td>
<td>Mainline, regional, urban and suburban</td>
<td>Mainline, regional, urban and suburban operation determined by underground sections, tunnels and/or elevated structures without any means for safe side evacuation from the vehicles</td>
</tr>
</tbody>
</table>

Table 5 – Operation categories 1 and 2 according to CEN/TS 45545-1

The operation categories 1 and 2 of rail vehicles are quite similar to the operation conditions of buses as well as the design categories D, S and N (see Table 6).

<table>
<thead>
<tr>
<th>Design category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Vehicles forming part of an automatic train having no emergency trained staff on board</td>
</tr>
<tr>
<td>D</td>
<td>Double decked vehicles</td>
</tr>
<tr>
<td>S</td>
<td>Sleeping and couchette vehicles</td>
</tr>
<tr>
<td>N</td>
<td>All other vehicles (standard vehicles)</td>
</tr>
</tbody>
</table>

Table 6 – Design categories according to CEN/TS 45545-1
The Hazard Level of a vehicle is regulated by the following matrix (see Fel! Hittar inte referenskälla.). For the operation category 1 and 2 the Hazard Levels 1 or 2 are requested.

<table>
<thead>
<tr>
<th>Operation category</th>
<th>Design category</th>
<th>N (Standard vehicles)</th>
<th>A (Automatic vehicles having no emergency trained staff on board)</th>
<th>D (Double decked Vehicle)</th>
<th>S (Sleeping and couchette cars double decked or single deck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HL1</td>
<td>HL1</td>
<td>HL1</td>
<td>HL1</td>
<td>HL2</td>
</tr>
<tr>
<td>2</td>
<td>HL2</td>
<td>HL2</td>
<td>HL2</td>
<td>HL2</td>
<td>HL2</td>
</tr>
</tbody>
</table>

Table 7 – Matrix of Hazard Levels according to CEN/TS 45545-2

To show the difference in the fire safety performances between train and bus interior materials the measured material data were evaluated according to the rail standard CEN/TS 45545-2 while the materials were taken from buses. First the heat release rates were determined which is based on the EN ISO 5660-1. The test duration amounts to 20 minutes for the determination of the ARHE(t)-value (Average Rate of Heat Emission a function of test time) and the MARHE-value (peak of measured ARHE-values). According to CEN/TS 45545-2 the limitation of the heat release takes place by the MARHE-value which does not have to exceed a corresponding threshold. Concerning the MARHE-value the requirement class also defines the irradiance level in the Cone Calorimeter (e.g. ISO 5660-1: 50 kWm$^{-2}$). The measured data are listed in Table 2 including their individual requirement number, the demanded irradiance level and the corresponding thresholds for Hazard Level 1 and 2. The coloring illustrates the applicability of investigated materials in rail vehicles. Red colored limits of HL1 or HL2 correspond to failed values. The green color indicates valid values.

<table>
<thead>
<tr>
<th>Material</th>
<th>Requirement No.</th>
<th>Irradiance [kW/m²]</th>
<th>MARHE [kW/m²]</th>
<th>Thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body insulation (1st)</td>
<td>R1</td>
<td>50</td>
<td>334,5</td>
<td>- 90</td>
</tr>
<tr>
<td>Body insulation (2nd)</td>
<td>R1</td>
<td>50</td>
<td>309,0</td>
<td>- 90</td>
</tr>
<tr>
<td>Floor covering</td>
<td>R9</td>
<td>25</td>
<td>32,5</td>
<td>- 50</td>
</tr>
<tr>
<td>Side panel (1st)</td>
<td>R1</td>
<td>50</td>
<td>64,8</td>
<td>- 90</td>
</tr>
<tr>
<td>Side panel (2nd)</td>
<td>R1</td>
<td>50</td>
<td>54,2</td>
<td>- 90</td>
</tr>
<tr>
<td>Flooring</td>
<td>R9</td>
<td>25</td>
<td>1,6</td>
<td>- 50</td>
</tr>
<tr>
<td>GRP part (1st)</td>
<td>R1</td>
<td>50</td>
<td>258,5</td>
<td>- 90</td>
</tr>
<tr>
<td>GRP part (2nd)</td>
<td>R1</td>
<td>50</td>
<td>280,9</td>
<td>- 90</td>
</tr>
<tr>
<td>Ceiling over seats (1st)</td>
<td>R1</td>
<td>50</td>
<td>247,2</td>
<td>- 90</td>
</tr>
<tr>
<td>Ceiling over seats (2nd)</td>
<td>R1</td>
<td>50</td>
<td>215,7</td>
<td>- 90</td>
</tr>
<tr>
<td>Ceiling over gangways (1st)</td>
<td>R1</td>
<td>50</td>
<td>307,7</td>
<td>- 90</td>
</tr>
<tr>
<td>Ceiling over gangways (2nd)</td>
<td>R1</td>
<td>50</td>
<td>255,5</td>
<td>- 90</td>
</tr>
<tr>
<td>Foam of seats (1st)</td>
<td>R20</td>
<td>25</td>
<td>309,2</td>
<td>75 50</td>
</tr>
<tr>
<td>Foam of seats (2nd)</td>
<td>R20</td>
<td>25</td>
<td>166,7</td>
<td>75 50</td>
</tr>
</tbody>
</table>

Table 2 – Results of Cone Calorimeter tests

The requirements for the heat release of Hazard Level 1 und 2 was only passed by the flooring, the floor covering and the side panel. The maximum heat release rate of the tested materials is more than 6 times higher than allowed in the CEN/TS 45545-2. Especially the high level of heat release rates generated by the burning seat foam and the ceiling material are very critical. So, a fire can spread very rapidly from seat to seat and along the ceiling with such materials.
**TOXICITY OF SMOKE GASES**

The severe bus fire in 2008 in Germany showed that especially the smoke is a threat to the passenger’s safety. Smoke gases had become quickly toxic and opaque which prevented a successful escape. After the bus fire several passengers were found still strapped to their seats. Incapacitation due to smoke inhalation came before they could even start to escape. In contrast to the bus interior materials the smoke production and toxicity is limited for train materials and has to be measured in the Smoke Density Chamber according to CEN/TS 45545-2. Therefore bus materials were also tested by us in the Smoke Density Chamber. The measured data are listed in Table including the calculated CIT-values (Conventional Index of Toxicity) after 4 and 8 minutes of testing. Additionally the toxic concentration limits of smoke gas components from the manufacturers Bombardier (SMP 800-C), Airbus (ABD 00031), Boeing (BSS 7239) and for ships (IMO MSC 61 (67) Annex 1, Part 2) as well as intoxication thresholds are also listed in the Table (grey colored and cursive) to assess the toxicity of smoke gases generated by burning bus interior materials. Yellow colored cells mark a gas concentration which generates symptoms of intoxication. Bright red colored cells indicate lethal gas concentrations. The red color indicates failed limits of HL 1 or HL 2; green color indicates valid values. The yellow color indicates exceeds of the concentration limits of at least one listed standard.

The toxic gas concentrations are measurements of single specimens (75 mm x 75 mm x thickness) in the Smoke Density Chamber (approximately 0.5 m³).

<table>
<thead>
<tr>
<th>Material (material requirement)</th>
<th>Components of CIT-value</th>
<th>CIT-value</th>
<th>Calculated CIT-value</th>
<th>HL1 (CEN/TS 45545-2)</th>
<th>HL2 (CEN/TS 45545-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First symptoms of intoxication</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMO MSC 61(67) Annex 1, Part 2</td>
<td>CO₂ [ppm]</td>
<td>1450</td>
<td>120</td>
<td>350</td>
<td>600</td>
</tr>
<tr>
<td>ABD 00031 (Airbus)</td>
<td>CO [ppm]</td>
<td>1000</td>
<td>100</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>BSS 7239 (Boeing)</td>
<td>NOₓ [ppm]</td>
<td>3500</td>
<td>100</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>SMP 800-C (Bombardier)</td>
<td>SO₂ [ppm]</td>
<td>90000</td>
<td>3500</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Lethal concentrations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body insulation (R1)</td>
<td>First symptoms of intoxication</td>
<td>20000</td>
<td>200</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Floor covering (R9)</td>
<td>8 min</td>
<td>6900</td>
<td>168</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>Ceiling above seats (R1)</td>
<td>8 min</td>
<td>35700</td>
<td>1122</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ceiling above gangways (R1)</td>
<td>8 min</td>
<td>15800</td>
<td>53</td>
<td>0</td>
<td>74</td>
</tr>
<tr>
<td>Foam of seats (R20)</td>
<td>8 min</td>
<td>14200</td>
<td>23</td>
<td>1</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 9 – Measured concentrations of toxic smoke gas components
According to the CEN/TS 45545-2 the evaluation of the smoke gas toxicity is performed by the CIT-value. From all bus interior materials the body insulation, the side panel, the GRP part and the foam of seats pass the requirements of the Hazard Level 1 and 2 which are essential for corresponding rail vehicles. The CIT-values of the investigated ceiling and flooring materials fail the limits. Regarding the concentrations of single smoke gas components the CIT-value method reveals a weakness in the evaluation of toxicity. Especially the measured data of the side panel which has a valid CIT-value according to the CEN/TS 45545-2 contains extremely toxic concentrations of single smoke gas components. Also the GRP part which has a valid CIT-value generates lethal concentrations of single toxic smoke gas components. Also the HCl-concentration in the smoke gas of a burning floor covering specimen exceeds the lethal concentration 81 times.

All tested bus interior materials generate hazardous till lethal concentrations of toxic smoke gases components. The limitation of toxic smoke by the CIT-value according to the CEN/TS 45545-2 is not very reliable, because toxic concentrations of single smoke gas components are not limited. Also the reliability of the Smoke Density Chamber has been questioned over the last years. So, for instance the European project Transfeu has one work package to enhance the testing procedures of the Smoke Density Chamber. The measurement results of this test procedure are still under discussion because the influence of the available oxygen in the chamber is not well defined in the test setup. The Smoke Density Chamber is principally an enclosed system with no further air supply during the test whereby the burning behavior of a specimen influences itself and the available oxygen in the chamber cannot be monitored or varied during the test. Also the CIT approach according to CEN/TS 45545-2 is a questionable evaluation method because results could be within the given limits although single smoke gas components can occur in a lethal dose.

Instead the toxic concentrations of single smoke gas components could be restricted. For instance the SMP-800-C from Bombardier would deliver proper concentration limits. Also the concentration limits of ship materials (IMO MSC 61(67) Annex 1, Part 2) and of the airplane manufacturers Boing (BSS 7239) and Airbus (ABD 00031), see figure 1, would suit.

A scientific based and more reliable method for restricting the toxicity in smoke gases is the FED (Fractional Effective Dose) concept. FED has been developed to predict mathematically the instant of time when unconsciousness or incapacitation would occur in a given environment. The FED concept takes the time of exposure and therefore the accumulation of toxic products into account. This approach is extremely valuable to predict the available escape time in case of fire.

It is also an attractive option to introduce a new testing method as the vitiated Cone Calorimeter approach. The Cone Calorimeter has a far more reliable test setup because the oxygen content can be monitored and adjusted in contrast to the Smoke Density Chamber. A new work item proposal has been introduced in ISO TC 92 SC1 (Fire initiation and growth) which reflects the need of a standardized test method using the vitiated Cone Calorimeter. The future results of this work can be used to implement a more reliable and realistic test procedure.

Concerning the investigation on the light transmission in smoke gases the optical density (Dₚ) and the cumulative value of specific optical densities in the first 4 test minutes (VOF4) were measured. The results are listed in Table 10 as well as the corresponding limits of the Hazard Level 1 und 2 according to CEN/TS 45545-2.
Regarding the optical density ($D_s$) only the body insulation and the foam of seats pass the requirements of Hazard Level 1 and 2.

Regarding the cumulative value of specific optical densities in the first 4 min of testing (VOF4) the body insulation and the floor covering are principally allowed for the operation in Hazard Level 1 and 2. But VOF4-thresholds do not exist for the floor covering and the foam of seats though the $D_s$-thresholds are partially exceeded.

In case of a city bus (if HL1 shall be applied, see Table ) the side panel might additionally be valid as a rail material.

In Table 11 all results of the experimental comparison (bus interior materials tested as materials for rail vehicles according to 45545-2) are summarized. The red color indicates invalid values, the green color indicates valid values and the yellow color indicates valid values for Hazard Level 1 but values which exceed the limits of Hazard Level 2.

In summary it can be said that almost all investigated bus interior materials fail the requirements of similar rail vehicles with Hazard Level 1 and 2 according to CEN/TS 45545-2. Only the tested side panel material passed at least the requirements of Hazard Level 1. Particularly the toxic smoke gases show that the fire safety requirements of current road vehicle standards are not adequate.

Table 10 – Measurements regarding the light transmission according to CEN/TS 45545-2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Body insulation (1st)</td>
<td>R1</td>
<td>334,5</td>
<td>0,3</td>
<td>127,5</td>
<td>260,8</td>
<td>No No</td>
</tr>
<tr>
<td>Floor covering (1st)</td>
<td>R9</td>
<td>64,8</td>
<td>0,6</td>
<td>560,2</td>
<td>Not required</td>
<td>Yes No</td>
</tr>
<tr>
<td>Flooring</td>
<td>R9</td>
<td>1,6</td>
<td></td>
<td>Not tested</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRP part (1st)</td>
<td>R1</td>
<td>280,9</td>
<td>0,2</td>
<td>1320,0</td>
<td>1843,9</td>
<td>No No</td>
</tr>
<tr>
<td>Ceiling over seats (1st)</td>
<td>R1</td>
<td>247,2</td>
<td>1,9</td>
<td>839,5</td>
<td>2389,9</td>
<td>No No</td>
</tr>
<tr>
<td>Ceiling over gangways (1st)</td>
<td>R1</td>
<td>307,7</td>
<td>2,9</td>
<td>622,5</td>
<td>2224,8</td>
<td>No No</td>
</tr>
<tr>
<td>Foam of seats</td>
<td>R20</td>
<td>309,2</td>
<td>0,3</td>
<td>100,5</td>
<td>Not required</td>
<td>No No</td>
</tr>
</tbody>
</table>

Table 11 – Summary of measurements according to CEN/TS 45545-2

In summary it can be said that almost all investigated bus interior materials fail the requirements of similar rail vehicles with Hazard Level 1 and 2 according to CEN/TS 45545-2. Only the tested side panel material passed at least the requirements of Hazard Level 1. Particularly the toxic smoke gases show that the fire safety requirements of current road vehicle standards are not adequate.
LARGE SCALE FIRE TESTS

In addition to the small scale tests also several large scale fire tests were performed on a city bus regarding the fire and smoke development in the passenger and engine compartment and also regarding the fire detection and extinguishing in the engine compartment. At first the smoke development in the passenger compartment was tested under different ventilation conditions. In different scenarios the spread of warm and also cold smoke were investigated in diverse combinations of opened or closed windows, door and ventilation flaps as well as air conditioning (see Figure 2).

![Figure 2 – Smoke spread tests in the passenger compartment](image)

Trials regarding the fire development combined with tests regarding the quality and the promptness of fire detectors and extinguishers were performed in the engine compartment (see Figure 3). Different fire detector methods (smoke, flame and heat detectors) and different extinguishing approaches (water mist, water droplets, foam and aerosol) were investigated with a completely running engine. Also the smoke gas spreading into the passenger compartment had been monitored and analyzed to determine the instant of time when the smoke gases of the burning engine compartment become hazardous for passengers. The engine was ignited by several ignition sources in several locations and the suppression systems were started manually. The running engine in combination with several ignition sources represents severe conditions for the suppression systems. Especially the air flow from the fan provided oxygen for the fire and challenged all tested extinguishing systems.

![Figure 3 – Fire and extinguishing tests in the engine compartment](image)

In another test a paper cushion was placed on a passenger seat to simulate arson according to the fire test for passenger seats (DIN 5510) and to determine the toxic smoke gases generated by a burning seat. The fire did not develop very fast (see Figure 4). Intermediate scale tests afterwards in the laboratory showed that the seat materials of the bus which was built in 1995 had a significant better fire performance than current materials do (see next section).

![Figure 4 – Burning paper cushion in a large scale fire test](image)

INTERMEDIATE SCALE FIRE TESTS

The fire safety performance of passenger seats was extra investigated because the seats represent the highest number of interior parts. Calorimeter tests with different types of passenger seats from city
buses (1995 model and 2005 model), a coach and a train (both constructions of foam) were performed in a modified Single Burning Item apparatus (see Figure 5). Paper cushions with a weight of 100 g according to DIN 5510 had been the ignition sources.

The differences in the fire behavior of the tested passenger seat types are significant (see Figure 5) and could also be shown in the measured heat release data (see Figure 6). All newer materials generated clearly higher levels of heat release rates. Only the train materials and the older city bus seat (1995) could present a better fire performance. It is presumed that the amount of plastics in busses must have been increased significantly in the last 15 to 20 years. The older city bus seat has an obviously better fire performance than the newer city bus seat. This phenomenon has to be investigated further.

**Figure 5 – Passenger seats in calorimeter tests**

**Figure 6 – Measured heat release rates of different passenger seats**

**NUMERICAL FIRE SIMULATIONS**

Numerical fire simulations have been also used to investigate the fire safety of busses. Several geometries and bus types equipped with different materials (e.g. normal and improved interior materials for busses or trains) were simulated with the version 5 of the Fire Dynamic Simulator (FDS). The material data came from the fire safety tests. The first simulation attempts were a rebuild of the severe bus fire in 2008 [9, 10, and 11]. Witness statements about the fire development announced a hard and rapid fire spread out of the lavatory through the passenger compartment (see Figure 7).
In the next steps the bus geometry was adapted to the original bus model with a luggage compartment. A bus model of the original bus type could be found in a game (Bus simulator 2010). This model also was used to simulate several different fire scenarios, e.g. fire origin in the back row of a bus equipped with interior materials for buses (Figure 8, left) and trains (Figure 8, right). The snapshots are at the time of 135 s after ignition. In this moment the fire has already spread to other seats and the ceiling has been ignited in bus equipped with bus interior materials. In the bus equipped with train materials only the ignition source burns and some smoke is in the passenger compartment. But the fire did not spread to other seats or to the ceiling.

Additionally to the fire tests in the engine compartment several numerical fire simulations were performed with the engine compartment test rig at SP (Sweden) to investigate and enhance the test-up (see Figure 10).

CONCLUSIONS
Studies show that bus fires occur very frequently, however most of them do not result in any personal damage. But in certain cases single bus fires can cause a large number of fatalities because of the rapid fire and smoke spread. Even for physically fit people escaping may become difficult or impossible. One cause of the severity of fires in modern busses turned out to be the materials the bus interior consist of. Over the past 20 years the amount of plastics in busses has increased significantly. The burning of these materials are responsible for rapid fire spread through the passenger compartment and large amounts of toxic smoke which prevents passengers to escape in time. In contrast the fire safety requirements of busses were derived from the American standard FMVSS 302 which was developed in the 1960s. The aim of these requirements was to prevent vehicle fires in consequence of smoking. However, most fires start in the engine compartment or due to electrical failure (as in the 2008 fire).

The comparison of fire safety requirements in different passenger transport sectors, i.e. train, maritime and aviation sector, shows that the requirements in the automotive sector are on a significantly lower level. In the other transport sectors the requirements for the flammability, the heat release rates and the smoke production and toxicity are significantly higher. Almost all tested bus materials failed the requirements for application in the train sector, although the operating conditions of trams and city busses, long-distance trains and coaches are absolutely comparable. The results of the experiments with bus interior material which were compared with existing rail standards show that it is necessary that the requirements for material used in busses have to be revised and improved.
PERSPECTIVE

The following measures are recommended to enhance the fire safety of busses:

• The flammability and the rate of heat release of all materials must be limited. The vertical flammability test should be the minimum for all bus interior materials as in the other transport sectors and the building sector. Numerical investigations showed the influence of the ceiling material on the fire spread through the bus. The rate of heat release can be limited as in the European regulations for trains according to CEN/TS 45545-2. Hazard Level 1 is applicable to city busses. But double deckers and coaches should be treated more carefully with Hazard Level 2. Also a calorimeter test bus seats are necessary because the seats are a significant part of the fire load.

• The application of smoke detectors in hidden areas is also recommended to enhance the available escape time by early fire detection. Also the development of a large fire unknown by the driver and the passengers is prevented. European regulations are probably effective in 2014/2015.

• The consideration of the fact that most bus fires start in the engine compartment and efficient extinguishing systems (e.g. SP METHOD 4912) should be mandatory for all busses. But also the efficient fire detection is needed for enhanced fire safety performance in busses.

• The limitation of smoke production and smoke toxicity for interior materials are necessary because often the smoke prevents the escape of passengers. One way could be to adopt again the requirements for trains. However, the Smoke Density Chamber as test method as well as the CIT value is questionable. A more realistic and reliable test method like the Vitiated Cone Calorimeter with a scientific developed FED approach to limit the smoke gas toxicity is preferable.

ACKNOWLEDGMENTS

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LITERATURE

[7] DIN 5510: Preventive fire protection in railway vehicles; levels of protection, fire preventive measures and certification, 1988, Beuth Verlag
Model scale metro carriage fire tests –
Influence of material and fire load

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SP Technical Research Institute of Sweden
Borås, Sweden

ABSTRACT
To study the fire spread in a metro carriage, fire tests in a scale model (1:3) were performed. A total of 10 tests were carried out to investigate the effect of material, fuel load, openings (doors and windows), and ignition location on the fire development. The fuel loads consisted of PUR seats, wall and floor coverings, and in some tests longitudinal wood cribs simulating luggage. Different parameters including heat release rate, gas temperature, gas concentration, heat flux and smoke density were investigated. The results show that the material and especially the luggage play a significant role in the fire development in the tested metro carriage. This proves to make the difference between minor fire spread and a carriage totally involved in the fire. The number and size of openings are also important for the fire development and maximum heat release rate. The focus of this paper is on the influence of the material and fuel load (luggage) on the fire development and fire spread.

Key words: metro carriage, fuel load, luggage, fire development, heat release rate

INTRODUCTION
A fire in a metro train can be hazardous to the passengers on the train and to people near the train, e.g. waiting on a station. A large fire can also affect infrastructure and installations. There is, therefore, a need for knowledge on both how a fire develops inside a metro train, how large such a fire can be and how a fire in a metro car can affect its surroundings. To deal with these problems, a research project called METRO was initiated. This is a multi disciplinary project including research areas such as: fire spread, design fires, evacuation, integrated fire control, smoke control, extra ordinary strain on construction, and fire and rescue operations. Several of these parts involve large scale or model scale experiments, e.g. large scale fire experiments [1-3]. This paper presents experiments performed in model scale [4].

The understanding of how a fire develops in a metro carriage has been studied previously in smaller scale (1:10) than was used in the test series presented here. The results indicate that the ventilation conditions inside a metro carriage are crucial for the fire development and spread [5]. Therefore, the carriage material, properties of the windows (and other openings), have a significant effect on the outcome of a fire. One reason for performing a series of model scale tests in an intermediate scale (1:3) was to confirm these results. Another important aim of the tests was to complement the large scale tests to be performed and the results were used in the planning of these large scale tests. The experimental results will also be used to develop engineering models.

The aim of the tests was to study the influence of material, fuel load, openings (doors and windows), and ignition location on the fire development and fire spread in a metro carriage. During the test series the effect of the material used on the walls, ceiling and floor, and extra fire load simulating luggage showed to be very important for the fire development. This is the focus in this paper.
METHODOLOGY

The methodology selected for the work was scale modelling, where the effects of variation of different parameters were studied. When using scale modelling it is important that the similarity between the full-scale situation and the scale model is well-defined. A complete similarity involves for example both gas flow conditions and the effect of material properties. The gas flow conditions can be described by a number of non-dimensional numbers, e.g. the Froude number, the Reynolds number, and the Richardson number. For perfect scaling all of these numbers should be the same in the model-scale model as in the full-scale case. This is, however, in most cases not possible and it is often enough to focus on the Froude number. This so called Froude scaling has been used in the present study, i.e. the Froude number alone has been used to scale the conditions from the large scale to the model scale and vice versa. More information about scaling theories can be obtained for example from references [6-9].

The model-scale railcar used in the study presented here was built in scale 1:3, which means that the size of the railcar is scaled geometrically according to this ratio. The main parameters considered in the study and how they are scaled between real scale and the model are presented in Table 1. Previous studies have proven that model-scale studies can give interesting results and give important information on fire behaviour when different parameters are varied [5, 10-12].

Table 1: A list of scaling correlations for the model tunnel.

<table>
<thead>
<tr>
<th>Type of unit</th>
<th>Scaling</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Release Rate</td>
<td>( \frac{Q_M}{Q_F} = \left( \frac{l_M}{l_F} \right)^{5/2} ) (1)</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>( \frac{V_M}{V_F} = \left( \frac{l_M}{l_F} \right)^{1/2} ) (2)</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>( \frac{t_M}{t_F} = \left( \frac{l_M}{l_F} \right)^{1/2} ) (3)</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>( \frac{E_M}{E_F} = \left( \frac{l_M}{l_F} \right)^3 ) (4)</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>( \frac{m_M}{m_F} = \left( \frac{l_M}{l_F} \right)^3 ) (5)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>( \frac{T_M}{T_F} = 1 ) (6)</td>
<td></td>
</tr>
<tr>
<td>Gas concentration</td>
<td>( \frac{Y_M}{Y_F} = 1 ) (7)</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>( \frac{P_M}{P_F} = \left( \frac{l_M}{l_F} \right) ) (8)</td>
<td></td>
</tr>
</tbody>
</table>

\( l \) is length scale. Subscripts M and F represent model scale and full scale, respectively.

One part of the scaling is to find materials suitable for the tests. It is difficult to find appropriate material that fulfils both the scaling of combustion properties and thermal properties. In the test report, a detailed analysis of the scaling of different parameters is presented [4]. Note that in the model scale tests presented here the scaling ratio is 1:3, and the analysis indicates that keeping the same materials will not result in significant difference in the test data. Therefore, the same materials as in full scale were used to some extent in the model scale tests to verify this postulation. The materials used were scaled geometrically (e.g. thicknesses) according to the length scale. The total energy content was also scaled. The test results are mainly used for the evaluation of effects when different parameters were varied.

EXPERIMENTS

Experimental set-up
The model-scale railcar was 7.27 m long, 1 m wide and 0.77 m high, see Figure 1, and was built in the large fire hall at SP. The corresponding dimensions in full scale were 21.8 m long, 3 m wide and 2.3 m high. The railway car used to design this scale model was a train type called XI. The X1 train was manufactured by Asea and built between 1967-1975. The X1 carriage has been used by for example the Stockholm Public Transport. A description of the full scale carriages can be found in publications on full scale tests [2-3].
The model-scale railcar was built on tables to get a better and more ergonomic working height and to have a completely horizontal surface. The tables had a framework of wood bars with the dimensions of 45 mm × 90 mm and a top of 22 mm particle board, forming the support for the floor of the railcar. The height of the railcar floor above the fire hall floor was 0.9 m. In the following the floor referred to means the railcar floor by default.

Figure 2 shows schematic drawings of the model-scale railcar. There are 6 doors in total, i.e. 3 doors on each side (DR1-DR3 and DL1-DL3), and 10 windows on each side (mainly those on the right side, WR1-WR10, were opened during the test series). Both ends of the railcar were closed. The two sides of the railcar are defined as left and right, respectively, as shown in Figure 2(b). The driver’s cabin was not modelled in the tests.

Fire load: The combustible material was mainly seats (PUR), but in some of the tests combustible inner lining on the walls and ceiling was installed (1 mm HPL, high pressure laminate, density of 1400 kg/m²), and combustible flooring in form of 17 mm pinewood plywood (10 mm + 7 mm; density 570 kg/m²) was used. In some tests, longitudinal wood cribs were also placed on the railcar floor to simulate the luggage carried by passengers and to correlate the total energy content with the one
estimated for the real scale X1 carriage. Different types of materials that were used in the test series are described below. In Table 3 the conditions for each test are presented, including the combustible material used.

**Walls and ceilings:** The railcar was constructed with material in two layers: an outer layer with 12 mm plywood and an inner layer with 15 mm non-combustible boards (Promatect H). In some tests, 1 mm thick HPL was mounted on the walls and the ceiling to provide a combustible surface.

**Floor:** Two different types of floors were used in the test series. In both cases, the floor was made of 22 mm fibre board and 6 mm Masterboard as the basic layer. When a non-combustible floor was used, an extra 6 mm Masterboard and 10 mm Promatect H were put on the floor. When a combustible floor was used, two boards of pine plywood were placed on the basic layer to obtain a thickness of 17 mm (10 mm + 7 mm), which is approximately the same height of the floor as in the case with non-combustible material.

**Seats:** The seats had a framework constructed using reinforcement bars and steel sheets with a thickness of 1 mm. This framework made it possible to use the same seat frames for all tests and only change the PUR covering. The seats consisted of two layers of PUR: one with a thickness of 2 cm and one with a thickness of 1 cm, and the seat back consisted only of 1 cm thick PUR (see Figure 3). There were 22 “double” seats and 18 “triple” seats in the railcar. The surface dimensions of the double seats were 0.307 m × 0.14 m for the seat and 0.273 m × 0.13 m for the back. The corresponding dimensions for the triple seats were: 0.455 m × 0.14 m and 0.425 m × 0.13 m, respectively. The PUR seats were used in all tests. The PUR had a density of 48 kg/m³ and a hardness (according to SS-ISO 2439) of 110 N.

![Figure 3 Photos of the seat frame with and without PUR.](image)

**Material tests:** To characterize the different materials described above, they were tested in the cone calorimeter. The results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Variable / Material</th>
<th>HPL</th>
<th>Plywood</th>
<th>PUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation (kW/m²)</td>
<td>35</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>t_ign (s)</td>
<td>NI</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>t_ext (s)</td>
<td>-</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>t_test (s)</td>
<td>600</td>
<td>300</td>
<td>1980</td>
</tr>
<tr>
<td>HRR_max (kW/m²)</td>
<td>18.30</td>
<td>133.03</td>
<td>187.09</td>
</tr>
<tr>
<td></td>
<td>220.11</td>
<td>443.83</td>
<td>517.49</td>
</tr>
<tr>
<td>Average MLR (g/m²/s)</td>
<td>3.24</td>
<td>5.44</td>
<td>6.32</td>
</tr>
<tr>
<td></td>
<td>8.31</td>
<td>14.2</td>
<td>15.6</td>
</tr>
<tr>
<td>ΔHc (MJ/kg)</td>
<td>2.63</td>
<td>7.61</td>
<td>11.91</td>
</tr>
<tr>
<td></td>
<td>12.77</td>
<td>26.50</td>
<td>25.33</td>
</tr>
<tr>
<td>MARHE (kW/m²)</td>
<td>6.2</td>
<td>39.8</td>
<td>85.1</td>
</tr>
<tr>
<td></td>
<td>142.4</td>
<td>335.2</td>
<td>382.8</td>
</tr>
</tbody>
</table>

NI = No ignition

**Luggage:** In some tests longitudinal wood cribs were placed on the floor to simulate the luggage
carried by passengers. These wood cribs had the dual purpose to better correlate the total energy content compared to a real X1 train. The wood crib had the dimensions of 1 m (L) × 0.22 m (W) × 0.072 m (H), as shown in Figure 4. The cross-section of each stick was 0.018 m × 0.018 m. Seven wood cribs were placed in line on the railcar floor under each row of seats, giving a total of 14 wood cribs (see Figure 5). The weight of each wood crib was on average 2580 g and had an average moisture content of 11.4 %. The maximum HRR of each such 1 m wood crib was estimated to be 0.13 MW. Note that not all wood cribs were burning at the same time during a test.

![Figure 4](image1.png)  
**Figure 4**  
Longitudinal wood cribs simulating luggage. There were 14 wood cribs (7 under each row of seats) placed at the floor to cover the whole railcar.

![Figure 5](image2.png)  
**Figure 5**  
Two series of longitudinal wood cribs placed on the floor to simulate the luggage.

Ignition sources: Small wood cribs were used as the ignition source. The test series was not to assess the ignitability of the fabric of the seats and therefore ignition sources of larger sizes were used to represent e.g. luggage. The HRR of 300 kW (in full scale) was used as a standard value. This represents approximately 20 kW in the model scale. The ignition sources consisted of 0.12 m high wood cribs made of wood sticks with a cross section of 0.01 m × 0.01 m. The wood cribs had in total 12 layers with four sticks in each layer, see Figure 6.

![Figure 6](image3.png)  
**Figure 6**  
Geometry of the wood cribs used as ignition source.

Pieces of fibre-board were soaked in heptane and placed under the wood cribs to ignite them. Two pieces of fibre-board measuring 0.1 m (L) × 0.01 m (W) ×0.01 m (H) were soaked in 3 mL heptane each. These replaced the two centre wooden sticks in the lowest layer of the wood crib (marked with darker colour in Figure 6 a)). The wood cribs used for ignition were placed on different seats during the test series, i.e. at F1 to F4, as shown in Figure 2 b), Figure 5 and described in Table 3. The heat release of the wood cribs used for ignition was determined by performing a calibration test in a cone calorimeter (see Figure 7). The maximum heat release rate in this test was 22 kW.

For ignition of the longitudinal wood cribs, larger pieces of fibre board measuring 0.2 m (L) × 0.07 m (W) ×0.012 m (H), soaked in 15 mL heptane each, were used. The pieces were placed beneath the longitudinal wood cribs on the railcar floor, i.e. at F5 and F6 (or F7 and F8 when alternative position
of ignition was used, see Test 9 in Table 3), as also shown in Figure 5. Four such large pieces of fibre board (two under each row) were used in each test with longitudinal wood cribs.

![Figure 7](image)

**Figure 7** Calibration of the ignition wood crib.

In Test 4, several wood cribs were placed on the floor, between the seats, to investigate the fire spread. There were no ignition source for these wood cribs, but they were only used as targets for the fire spread [4].

**Measurements**

Various measurements were conducted during each test. The measured parameters included: heat release rate, gas temperature, gas concentrations, heat flux and smoke density.

The heat release rate was measured using the SP large scale calorimeter beneath the ceiling of the main fire hall. All the smoke was collected by the hood and then guided to the measurement station in the exhaust duct. The properties of the fire gases were measured in the duct. Then the heat release rate could be calculated using the oxygen consumption technique [13-16].

The gas temperature was in most positions measured using welded 0.25 mm type K thermocouples. The locations of the thermocouples are shown in Figure 8. Most of the thermocouples were placed on the centre line of the model railcar and at 0.092 m beneath the ceiling. Seven thermocouple trees were used with thermocouples at heights of 0.092 m, 0.23 m, 0.383 m, 0.537 m, 0.675 m, to measure the vertical temperature distribution inside the railcar. Heat fluxes outside the railcar were measured using plate thermometers [17-18]. In total four plate thermometers were used, see Figure 8.

![Figure 8](image)

**Figure 8** The layout of measurement positions and identification of the instruments in the tests.

Gas concentrations (O₂, CO₂ and CO), were measured at the centre line of the railcar and 2.54 m from the left edge (x=2.54 m at position 9 in Figure 8) at heights of 0.092 m (not O₂), 0.383 m and 0.675 m above the floor. The smoke density was measured by laser/photocells at the centre line of the railcar and 2.25 m from the left edge (x=2.25 m at position 8 in Figure 8) and at heights of 0.092 m, 0.383 m and 0.675 m above the floor.
In this paper the focus is on the fire spread and maximum size of the fire and, therefore, mainly the HRR results are presented and discussed. More details on the results are given in the test report [4].

Experimental procedure

A total of ten tests were carried out. A summary of the tests is presented in Table 3. More details on the test conditions for each test are also given in the test report [4].

The wood cribs used as ignition sources were dried at 60 °C in a furnace for at least 24 h before the tests. The pieces of fibre board were soaked in heptane immediately prior to each test, placed in position and then ignited.

Different fire loads, openings and fire sources were tested. All three right doors, i.e. DR1, DR2 and DR3, were open during most of the tests. In Tests 3 to 5 and Test 10, the non-combustible wall materials (calcium silicate board), were changed to High Pressure Laminate (HPL). In Test 9, the wood cribs used for ignition were moved to fire source 4 (F4) and the ignition rectangles of fibre board was also moved (to F7 and F8). In Test 10, all six doors were open. The details for each test are given in Table 3.

Table 3 Summary of the metro railcar tests.

<table>
<thead>
<tr>
<th>Test no</th>
<th>Linings and floor covering</th>
<th>Ignition source and other fire load a</th>
<th>Openings</th>
<th>Extinguish time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wood crib (F1)</td>
<td>DR1, DR2, DR3</td>
<td>18 min</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Wood cribs (F1, F2, F3)</td>
<td>DR1, DR2, DR3</td>
<td>18 min</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1, F2, F3)</td>
<td>DR1, DR2, DR3</td>
<td>22 min</td>
</tr>
<tr>
<td>4</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1, F2, F3)b</td>
<td>DR1, DR2, DR3</td>
<td>20 min</td>
</tr>
<tr>
<td>5</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood crib (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3</td>
<td>27 min</td>
</tr>
<tr>
<td>6</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1</td>
<td>55 min</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3, WR1, WR2, WL1 and WL2c</td>
<td>32 min</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3, floor openinga</td>
<td>65 min</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Wood cribs (F4), Longitudinal wood cribs (F7 and F8)</td>
<td>DR1, DR2, DR3</td>
<td>63 min</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>HPL on walls and ceiling, plywood on floor</td>
<td>Wood cribs (F1), Longitudinal wood cribs (F5 and F6)</td>
<td>DR1, DR2, DR3, DL1, DL2, DL3</td>
<td>54 min</td>
</tr>
</tbody>
</table>

a The location of the ignition source can be found in Figure 2 b) and Figure 5.
b Five wood cribs on the floor.
c DR1-DR3 were open at the beginning while WR1, WR2, WL1 and WL2 were opened 15.5-16 min after ignition.
d A special opening on the floor was opened, as shown in Figure 2 b) and Figure 5 and as a dotted square in the left part of the drawings. The opening was 0.2 m × 0.2 m and was placed 0.1 m from the short wall.

At the end of each test, the fire was extinguished using water spray before self-extinguishment in order to protect the model railcar. In Test 5 to 7, the fires might have been extinguished somewhat
The focus of this paper being the influence of the material and fuel load (luggage) on the fire development and fire spread means that tests 2, 3, 4, 5 and 8 are of greatest interest to present and discuss in the results and discussion chapter below, and the focus will be on these tests.

RESULTS AND DISCUSSION

This paper focuses on the fire development and HRR results. Results from other measurements can be found in the test report [4]. The maximum HRR and time to maximum for some selected tests are presented in Table 4.

Table 4 Summary of maximum HRR for selected tests.

<table>
<thead>
<tr>
<th>Test no</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRR max (kW)</td>
<td>90</td>
<td>152</td>
<td>135</td>
<td>760</td>
<td>469</td>
</tr>
<tr>
<td>Time to HRR max (min)</td>
<td>3.7</td>
<td>2.5</td>
<td>3.0</td>
<td>27.3</td>
<td>54.5</td>
</tr>
</tbody>
</table>

In Tests 5 and 8, one ignition wood crib was used, while three ignition wood cribs were used in Tests 2, 3 and 4. There is a significant difference between Tests 3 and 4 on one hand and Test 2 on the other hand. Wall and ceiling lining were used in Tests 3 and 4. The maximum HRR is higher and was reached faster in Test 3 and Test 4 compared to Test 2. The material (HPL) on the walls and ceiling was very difficult to ignite and outside the carriage model it was not possible to get it to continue to burn if only a small ignition source (e.g. lighter) was use. Still when mounted on the surfaces in the scale model it contributed to the fire development and size of the fire.

As has been shown in some real scale tests [1], it was difficult to get the fire to spread between different seats, but as the fire spread in the luggage also the seats became involved in the fire and contributed to the size of the fire. It was also difficult to get the fire to spread from a seat to wood cribs on the floor between the seats. This suggests that if the initial fire is small and no flammable fuel is near the ignition source, fire spread would probably not occur. On the other hand fire spread could occur if the fuel load in form of luggage is large enough.

Figure 9 A comparison of the heat release rate in Test 3 without the longitudinal wood cribs and Test 5 with the longitudinal wood cribs.
It was observed in the present test series that the fire in Test 2 to Test 4 did not spread to the neighboring seat. Note that there was no longitudinal wood crib in these tests. The corresponding maximum heat release rates are lower than approximately 150 kW. This indicates the significance of the longitudinal wood cribs in the fire development. In addition, it suggests that if the initial fire is too small and insufficient combustible material is available in the vicinity of the ignition, fire spread will probably not occur.

Figure 9 shows a comparison of the heat release rate in Test 5 with longitudinal wood cribs (simulating the luggage fire load) and Test 3 without. The only difference between these two tests is the presence of longitudinal wood cribs in Test 5. It was observed that in Test 3 the fire did not spread to the neighboring seat. Therefore, the maximum heat release rate was as low as 150 kW.

Comparing the heat release rates in Test 2 and Test 3, there was a clear, although not very large, difference both in maximum measured HRR and in the shape of the curve, i.e. the addition of a combustible wall lining had an effect on the HRR. The fire spread to the lining in Test 3 and Test 4 was limited as was the overall fire spread in these tests. However, comparing the heat release rates in Test 5 and Test 8, see Figure 10, shows that the maximum heat release rate in the test with the linings and coverings (Test 5) is at least 70 % higher than without them. The wall and ceiling linings seem to be very important for the initial fire spread and speed of the fire development. Note also that in Test 5, about 60 % of fuel load consisted of the coverings, especially the floor covering. In other words, the total fuel load in Test 5 is about 2.5 times that in Test 8. This should, however, mainly affect the maximum HRR and total energy released, and not the initial fire spread and development.

![Figure 10](image-url)  
*Figure 10 A comparison of the heat release rate in Test 5 and Test 8 with different covering settings.*

**CONCLUSIONS**

A total of ten tests were carried out to investigate the effect of material, fuel load, openings (windows, doors and other openings) and ignition location on the fire development in a metro carriage. The focus of this paper is the effect of the materials and fuel load.

The fuel load plays the most important role in the fire development in the performed metro carriage scale-model tests. In the tests, the most important part of fuel loads for fire spread is the longitudinal wood cribs. Without the long wood cribs simulating the luggage, the fire did not spread between the seats. This proves the importance of the luggage in a rail carriage, both for the fire spread and for the total fire load. In most fire tests performed and reported in the literature luggage is not included. It is
important to understand that even good quality material could probably burn and contribute to the fire if supported by other fire loads, e.g. luggage. The lining material could also influence the effect of the luggage. Even though the wall and ceiling lining material used in the presented tests was difficult to ignite, it proved important for the fire spread. The interaction between luggage, lining material and seats, therefore, can have a significant influence on the fire spread and maximum size of a fire in a metro carriage.

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Quantification of Rapid Transit Vehicle Design Fire Heat Release Rates

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ABSTRACT

One of the most important factors in the fire engineering design of rapid transit systems is the quantification of vehicle design fires. Computational fluid dynamics (CFD) fire modelling techniques enable the prediction of design fire heat release rates for these vehicles, while accounting for propensity for ignition, initial fire size, initial fire location, complex train and tunnel geometries, tunnel and train ventilation conditions, and suppression systems. This is an advantage over historical design fire estimation methods, which do not account for the majority of these factors.

Application of CFD based flame spread modelling techniques in a risk based framework allows the likelihood, consequence and risk of design fire scenarios to be assessed. This enables a pragmatic approach to fire safety design, as the consequence of the fire scenarios can be considered in the context of the associated risk and the effectiveness of various risk mitigation strategies can be evaluated, optimising the overall design.

Keywords: rapid transit vehicle, design fire, heat release rate, risk analysis

INTRODUCTION

Quantification of vehicle design fires is an important element of the design of emergency ventilation systems for stations and tunnels of rapid transit systems. The design fire growth rate and peak heat release rate (HRR) are two key parameters that significantly influence the design. A number of different methods of analysis for quantifying rapid transit vehicle design fires are available, which have varying levels of predictive capability and complexity. The method selected can influence holistic design objectives as, if the design fire is inaccurately quantified, the ventilation system may be either under designed and present a life safety risk, or overdesigned and result in unnecessary capital expenditure.

HISTORICAL DESIGN FIRE ESTIMATION METHODS

Documented design fire peak heat release rates assumed in the design of rapid transit systems around the world have ranged from approximately 5 MW to 31 MW [1]. The historical methodologies applied to establish these HRR’s have typically relied either upon experimental observations, or calculation methods based on simplistic assumptions for fire growth that focus on the post-flashover period of fire development, during which time all compartment lining materials are assumed to burn simultaneously.
Experimental tests and historic fires

Physical testing of exemplar rapid transit vehicle train cars is the most accurate way to quantify the design fire heat release rate. However, the prohibitive costs, specialist facilities and timeframes required, mean that full scale physical testing is primary used for research.

Experimental results for fire incidents involving single rapid transit train cars have reported peak HRR values ranging from 5 MW to 77.4 MW [1,2,3,4,5,6]. For design purposes, these experimental values are useful as an order of magnitude estimate of peak HRR, but are only representative, as train construction materials are constantly evolving (i.e. improved fire resistance) and vary greatly between projects.

Traditional method

One of the first methods applied to estimate the HRR of post-flashover fires in rapid transit vehicles was the traditional (or average HRR) method [7]. The fuel load within a single train car is divided by the expected burn duration, assuming a constant fire HRR, as indicated in Eq. (1).

$$\dot{Q}_{ave} = \frac{E}{t_b}$$

where:

- \(\dot{Q}_{ave}\) = average heat release rate (kW)
- \(E\) = total fuel load (kJ)
- \(t_b\) = expected burn duration (s)

The fuel load is calculated from an evaluation of the mass of fuels and the associated heat of combustion, which can be determined experimentally or from literature. The train car burn duration is established from observations of historical train fire incidents and multiple train car involvement can be accounted for by offsetting the heat release rate and burnout of subsequent train cars [1].

Summation method

The summation method [8] uses bench scale (Cone Calorimeter [9]) experimental data to predict the peak heat release rate of post-flashover fires in train vehicles. This method assumes that all surfaces within a train car are burning simultaneously. The overall heat release rate of the entire train car is predicted based on the summation of the heat release rate time histories (established from using bench scale tests) multiplied by the area of each surface, as indicated in Eq. (2).

$$\dot{Q}_{(t)} = \sum \left( A_i \dot{q}_{i(t)}^* \right)$$

where:

- \(\dot{Q}_{(t)}\) = heat release rate time history (kW)
- \(A_i\) = area of surface (m²)
- \(\dot{q}_{i(t)}^*\) = heat release rate per unit area time history (kW/m²)
- \((t)\) = function of time (s)

Ventilation method

The ventilation method predicts the train fire heat release rate based upon the available ventilation openings, such as doors and windows, as indicated in Eq. (3) [4]. For fires nearing flashover and post-flashover, the mass flow rate of air into an enclosure has been found to be dependent on the available openings, which in turn influences the burning rate within the enclosure [10,11]. The ventilation dependent correction factor accounts for the combustion of volatiles that occurs outside of the enclosure [12], but literature that quantifies correction factors for rapid transit vehicles is limited [4].
Zone models

Single-layer post-flashover zone models have been used to predict the flame-spread and overall HRR within enclosures, such as rapid transit vehicle cars [13,14]. These models predict the interrelationship between compartment temperatures, airflow rates, and the burning rate, based on properties established from bench scale experiments. Initial ventilation conditions are specified, and window failure is predicted based on predicted compartment thermal conditions.

Limitations of historical methods

Historical methods used to estimate rapid transit vehicle design fire HRR’s provide a first order approximation, but are unable to account for many significant factors that impact the propensity and rate of fire development. The traditional, summation and ventilation design fire estimation methods use burning duration estimates, or superposition of Cone Calorimeter curves, to predict the peak HRR. The underlying assumption in these methods is that all interior lining materials in a single train car burn simultaneously, but this does not account for the incipient burning period, or the variations of the incident heat flux that occur during the initial growth stages of the fire. Therefore, these simplistic methods are unable to evaluate the propensity for fire development, accurately predict the design fire growth rate, or evaluate the likelihood for fire spread between train cars. In addition, the traditional and ventilation methods predict the average heat release rate and do not account for temporal variations or peaks in the HRR.

All of the historical calculation methods, including zone models, are unable to accurately predict or account for the influence of tunnel geometry, forced ventilation, or active fire suppression systems, all of which have a significant influence on the heat release rate in rapid transit vehicles. Tunnel geometry (including gradient and dimensions) can influence flame spread rate and peak heat release rate, due to the buoyancy effects of heated combustion gases and radiation feedback from tunnel linings and combustion gases [1,15,16,17,18]. Longitudinal tunnel ventilation systems are commonly used in rapid transit systems to control smoke movement and maintain tenable evacuation routes in fire emergencies [19,20]. Recent research has demonstrated that forced tunnel ventilation airflows can increase the peak fire HRR, due to the increased fire spread rate and availability of oxygen for combustion [5,6,17,18,21]. Modelling the effectiveness of fire suppression systems for rapid transit systems is complex as it is dependent upon the initial fire size, fire location and the coverage area and discharge characteristics of the suppression system.

To overcome limitations of historical calculation methods, advanced analysis techniques can be applied to predict the HRR for rapid transit vehicles and evaluate the impact that initial fire size/location, construction material ignition propensity, tunnel geometry, vehicle ventilation conditions, emergency ventilation system conditions and suppression systems have on overall fire performance.

ADVANCED METHODS

Computational fluid dynamics (CFD) models solve a form of the Navier-stokes equations on a numerical grid of elementary control volumes to simulate the interaction of liquids and gases with surfaces, which represent solids. CFD models are commonly used to predict the smoke movement resulting from a design fire with a specified heat release rate. Recent advances in flame spread
modelling and pyrolysis capabilities of CFD models, such as the Fire Dynamics Simulator Version 5 (FDS) [22], FireFoam [23] and Gpyro [24], have extended their application as predictive fire modelling tools. They can now be used to predict design fire HRR time histories (with growth rates, peak, and decay phases) once appropriate solid-phase burning characteristics have been established.

The CFD flame spread modelling techniques enable the prediction of rapid transit vehicle design fire HRR time histories and directly account for the propensity for ignition, initial fire size, initial fire location, complex train and tunnel geometries, vehicle and tunnel ventilation conditions, and suppression systems. A CFD representation of a rapid transit vehicle is presented in Figure 1 below. Although discussed in the context of rapid transit vehicles, these CFD based fire modelling techniques are equally applicable to other transit vehicles such as buses and airplanes.

(a) (b)

Figure 1: A CFD FDS model of rapid transit vehicle (a) isometric exterior, (b) isometric view inside the vehicle.

Methodology

Fire growth modeling requires effective material properties that characterize each combustible solid in the vehicle, including floor, wall, ceiling and seating materials. Unfortunately, existing input data in the literature is insufficient for specific application using most practical CFD flame spread modelling techniques and there is no standardized method for determining all of the material properties required for fire modelling [38]. Therefore, it is necessary to use bench scale experiments supplemented by numerical techniques to derive the material thermal, ignition, pyrolysis and combustion parameters.

Bench scale experiments are typically completed with the Cone Calorimeter [9], as shown in Figure 2 below. Material samples (with an area of 100 mm x 100 mm) are burned for a range of radiation exposures from 10 kW/m² to 75 kW/m², representing thermal exposures indicative of pre- and post-flashover compartment fire conditions. The testing is used to establish the HRR time histories, mass loss rate time histories, smoke production rate, and heat of combustion.

To predict fire growth, two different CFD based flame spread modelling approaches are possible. Either the material burning rate can be specified directly from experimental results based a specified level of radiation exposure, or alternatively, ‘effective’ material pyrolysis properties are used in conjunction with the model feedback to determine fire spread and growth.

Once the modelling parameters have been established through bench scale experimental testing, comparisons with partial or full-scale train fire experiments can further validate model accuracy [38], which is important if the models are used as a predictive tool.
Figure 2: (a) Schematic view of Cone Calorimeter [25], (b) Photo of material sample burning in Cone Calorimeter test apparatus and specimen holder [26].

Specified burning rate

For specified burning rate CFD flame spread modelling, ignition and thermal properties of the vehicle lining materials are derived from Cone Calorimeter testing over a range of exposure heat fluxes coupled with a heat conduction analysis [27]. The specified burning rate CFD modelling approach has been adopted for the analysis of residential, commercial and industrial facilities [28,29,30,31,32] and to predict the heat release rate of rapid transit vehicles [1].

The burning rate time history specified for each surface material is selected to correspond with the location/orientation and represent post-flashover radiation exposure conditions (for example 20 kW/m² for floors, 35 kW/m² for walls and 50 kW/m² for ceilings) [8]. Flame spread to adjacent surfaces is predicted as combustible surfaces on the numerical grid reach their associated ignition temperature, and ignite and burn with a specified heat release rate time history.

Pyrolysis modelling

Pyrolysis modeling is an alternative approach to flame spread modelling that allows the burning rate to vary locally with the magnitude of the received radiation. The CFD pyrolysis modelling approach has been successfully validated against experiments involving real-scale combustible wall assemblies [37] and real-scale rapid transit vehicle mock-ups [38].

Due to the numerous input quantities required for pyrolysis modelling, and the difficulty in measuring these properties directly from bench scale experiments, it is often necessary to work backward from bench scale flammability experiments. For this approach, experimental measurements of surface temperature and back-face temperature are required in the Cone Calorimeter testing, in addition to the quantities normally measured (mass loss rate, heat release rate, mass extinction, heat of combustion).

To establish the effective material pyrolysis properties, numerical optimization methods, known as stochastic search and optimization tools, are adopted. Numerical optimization methods include genetic algorithms (GA) [33,34] and the shuffled complex evolution (SCE) methodology [35], but it has been demonstrated that the SCE method is the most efficient optimization technique currently available for this process [36].
These numerical optimization methods utilize a random number generator to guess hundreds of different combinations of model input parameters within verifiable uncertainty bands. Each parameter set is then passed to the pyrolysis model and used to simulate the Cone Calorimeter outputs of mass loss, top surface and back surface temperatures. The CFD model and experimental outputs for mass loss rate, surface temperature and back-side temperature are compared and the “fitness” of each parameter set is determined by quantifying how well the pyrolysis model calculations match the experimental data. An iterative process is adopted and convergence is achieved when there is no additional improvement in the fitness of the outputs. The final set of effective material properties represents the “best fit” over the range of tested heat fluxes. Material properties should be optimized over a wide range of heat flux levels so that the solid-phase pyrolysis is well predicted.

**Limitations of advanced methods**

The primary limitation of CFD based flame spread modeling is the lack of validated input data in the literature and the cost of deriving and validating this data through experimental testing. However, to limit the level of complexity and meet a point of diminishing return, composite materials are treated as a lumped equivalent solid (with averaged thermal, pyrolysis and/or combustion properties) instead of separately evaluating the properties of individual layers.

A limitation of the specified burning rate methodology is that, following ignition, the burning rate of each combustible surface is pre-defined and does not vary with the actual level of received radiation, which may over or under-estimate the burning rate obtained from real scale experiments.

**RISK BASED CONTEXT**

Risk assessments are used to identify issues that represent vulnerabilities or weaknesses, analyse risks to determine the level of risk, and evaluate risks by comparing risk analysis results with acceptable risk criteria. Risk treatment strategies are evaluated iteratively until the level of risk is reduced to acceptable levels.

Risk assessments add value in the context of a design fire HRR assessment of rapid transit vehicles, as they incorporate likelihood/probability in the determination of credible design fires. Historical analysis techniques assume that a large fire will occur; however, historical global operational system data has indicated that modern rapid transit systems have experienced few catastrophic incidents. Most of the historical analysis techniques do not evaluate the influence of ignition source size and material fire spread propensity, which both greatly effect fire development. Omission of these critical components of fire development over-estimates the actual or perceived risk. Consideration of these factors, either qualitatively or quantitatively, provides a more holistic determination of the risk and a more comprehensive assessment of mitigation strategies.

The risk assessment process described below, for the fire engineering design of a rapid transit system, is based on the methodologies discussed by Bukowski [40], the American Public Transportation Administration (APTA) [41] and NFPA 551 [42]. The terminology is adopted from ISO 31000 [43] and the Department of Homeland Security (DHS) Guidelines [44]. Applicable industry guidelines are APTA, US Federal Regulations [45], SFPE Handbook [40, 46], EN 45545 [47], ICC Performance Based Code [48], and the Fire Engineering Design Guide [10].

**Establish the context**

A risk based fire engineering assessment can form a subset of a broader project wide risk assessment. To establish the context, risk assessment performance objectives should be identified in conjunction with the client, approval authorities and key stakeholders. For fire engineering risk assessments, the primary objectives are typically life safety (protection of passengers, employees and emergency responders) and capital/operational costs, but consideration should also be given to property protection, business continuity, system downtime, and intangible factors such as public perception.
Identify risks

A review of historical system operational data can be useful in the identification of ignition source HRR, ignition source location and the associated likelihood/frequency of different fire scenarios. The likelihood/frequency of initiating fires should be quantified if possible, but, where insufficient statistical data is available, can be described qualitatively, as indicated in Table 1 [39]. For rapid transit systems, the relative frequency would have units of events per year, and thus an occasional/likely event would be one that is observed in a person’s lifetime [39].

Table 1: Likelihood/frequency classification [39].

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Remoteness Description</th>
<th>Relative Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 - Frequent</td>
<td>Certain</td>
<td>$10^4$</td>
</tr>
<tr>
<td>4 - Probable</td>
<td>Almost Certain</td>
<td>$10^3$</td>
</tr>
<tr>
<td>3 - Occasional</td>
<td>Likely</td>
<td>$10^2$</td>
</tr>
<tr>
<td>2 - Remote</td>
<td>Seldom</td>
<td>$10^1$</td>
</tr>
<tr>
<td>1 - Improbable</td>
<td>Unlikely</td>
<td>1</td>
</tr>
</tbody>
</table>

Typical initiating fire sources include electrical malfunction, mechanical fault and arson. Factors requiring consideration when defining initial fire scenarios include fire source location, initial fire heat release rate, interior lining materials, ventilation conditions, and fire suppression systems.

Consideration should also be given to the objective of the engineering assessment. For example, if the intent is to compare the fire performance of two wall lining panels, fire scenarios would consider one specific arrangement with different fire locations and a range of initiating fires.

Analyse risks

To evaluate the consequence/severity of a fire resulting from the selected initial fire scenarios, advanced methods of analysis involving a combination of bench scale fire testing and CFD based flame spread modelling can be utilised (as discussed above). By using flame spread modelling, it is possible to evaluate the impact of initial fire size/location, interior lining material properties, tunnel geometry, ventilation conditions and suppression systems on overall fire performance.

For the fire retardant construction typical of rapid transit vehicles, different initiating fires are expected to result in a varying degree of fire spread and a range of vehicle fire heat release rates. For example, more frequent initial fires, such as a small trash fire or electrical failure, may only result in local fire spread along a seat or up an adjacent wall before self-extinguishing. Alternatively, low frequency events involving larger initiating fires, such as an arson based gasoline pour, could be large enough to result in full vehicle involvement.

Once the overall fire behaviour has been quantified, the consequence/severity of the fire on the selected risk assessment performance objectives can be established. Example qualitative consequence score descriptions are presented in Table 2 below for life safety and property protection in rapid transit systems, but they can alternatively be quantified with regard to deaths/injuries and repair/replacement cost, respectively.
Table 2: Consequence score descriptions for life safety and property protection.

<table>
<thead>
<tr>
<th>Consequence Score</th>
<th>Description</th>
<th>Life Safety</th>
<th>Property Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 - Catastrophic</td>
<td>Loss of life or a change in a person’s lifestyle needs (i.e. long term hospitalization or disability).</td>
<td>Vehicle replacement required and potential for damage to station/tunnel infrastructure and widespread damage.</td>
<td></td>
</tr>
<tr>
<td>4 - Serious</td>
<td>Large numbers of passengers treated for smoke inhalation and severe burns.</td>
<td>Significant damage to more than 70% of the vehicle interior. Smoke and heat damage throughout. Replacement of the whole vehicle interior.</td>
<td></td>
</tr>
<tr>
<td>3 - Significant</td>
<td>Limited numbers of passengers exposed to smoke, minor treatment for smoke inhalation. No burns.</td>
<td>Damage to more than 30% of the vehicle. Smoke damage throughout. Seats and panels, light diffuser panes require replacement.</td>
<td></td>
</tr>
<tr>
<td>2 - Minor</td>
<td>Passengers exposed to smoke but able to evacuate without any need for further treatment.</td>
<td>Replacement of wall panels and seats local to the incident. No major capital cost to repair the vehicle.</td>
<td></td>
</tr>
<tr>
<td>1 - Negligible</td>
<td>Passengers not exposed to smoke.</td>
<td>No measurable damage to vehicle.</td>
<td></td>
</tr>
</tbody>
</table>

Evaluate risks

Risk is measured in terms of a combination of the consequence (what effect an event will have) and the likelihood (the frequency of the event) [39]. Depending on personal philosophies and society’s concerns, people will perceive risk differently [39], but the generalised risk profile in Figure 3 below indicates how risk is generally perceived.

![Risk profile showing tolerability of risk (modified from [39]).](image)

Low consequence events with low probabilities are acceptable and fall in the negligible region, high consequence events with high probabilities are not acceptable and fall in the intolerable region, and low consequence events with a high frequency of occurrence will have a similar risk to a high consequence event with a low frequency of occurrence. When the consequence reaches a certain maximum level, the risk will be intolerable no matter what the likelihood. Likewise, when the likelihood reaches a certain maximum, the risk will be intolerable no matter what the consequence. Risks that fall between these boundaries in the tolerable region are generally accepted by the public, but must be made “as low as reasonably possible” (ALARP) [39], requiring further analysis and consideration.
Risk criteria are terms of reference against which the significance of risk can be evaluated [43], allowing the risks to be evaluated and possible risk treatment strategies to be ranked and prioritized. Risk criteria are developed as a collaborative effort by the designer and the entities accepting the risk, typically the owner and key stakeholders. A qualitative risk scoring matrix, as per the example presented in Table 3 below, is a simple method for presenting risk criteria and classifying the acceptable levels of risk. Descriptions of the associated risk scores from this risk scoring matrix are provided in Table 4. The risk scores were calculated by multiplying the consequence and likelihood.

### Table 3: Risk Scoring Matrix.

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>1 - Improbable</th>
<th>2 - Remote</th>
<th>3 - Occasional</th>
<th>4 - Probable</th>
<th>5 - Frequent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consequence</td>
<td>1 - Insignificant</td>
<td>2 - Minor</td>
<td>3 - Major</td>
<td>4 - Severe</td>
<td>5 - Catastrophic</td>
</tr>
</tbody>
</table>

### Table 4: Risk Score Descriptions.

<table>
<thead>
<tr>
<th>Risk Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-25</td>
<td><strong>Unacceptable</strong>: Poses immediate threat to personal safety. Correct, control, or mitigate immediately.</td>
</tr>
<tr>
<td>8-12</td>
<td><strong>Acceptable short-term</strong>: May pose a threat to personal safety. Formulate corrective action plans and implement on a priority basis.</td>
</tr>
<tr>
<td>4-6</td>
<td><strong>Acceptable with management review</strong>: Deemed acceptable or unavoidable risk after review by key stakeholders. Formal documentation of acceptance necessary.</td>
</tr>
<tr>
<td>1-3</td>
<td><strong>Acceptable</strong>: Deemed to be an acceptable risk. Documentation of this acceptance is necessary.</td>
</tr>
</tbody>
</table>

### Treat risks

Risks that are identified to be unacceptable, or that require corrective action, need to be treated to reduce the level of risk to an acceptable level. Risk treatment methodologies include avoidance, where measures are taken to remove exposure, and mitigation, where the impact of a hazard is mitigated by reducing the likelihood, or reducing the consequence should the hazard be realized. Risk mitigation is an iterative process, involving the evaluation of the revised level of risk with the mitigation strategies in place, and is typically coupled with a cost benefit analysis to define the optimum risk mitigation strategy.

Strategies to treat the fire risk include reduction of the train flammability through selection of alternate construction materials, and provision of a suppression system to control fire spread, as indicated in Figure 4.

Using a risk based approach in the fire engineering design of rapid transit systems allows for the consequences of possible fire events to be placed in context, enabling a more pragmatic design approach. In addition, the effectiveness of various risk mitigation strategies can be evaluated directly in a risk based framework to optimise the overall fire safety design.
CONCLUSIONS

Computational fluid dynamics (CFD) flame spread modelling techniques enable the prediction of rapid transit vehicle design fire heat release rate time histories that account for the propensity for ignition, initial fire size, initial fire location, complex train and tunnel geometries, tunnel and train ventilation conditions, and suppression systems. This is an advantage over historical first order approximations, which are unable to account for these factors that have a significant impact on the propensity for, and rate of, fire development.

Flame spread modelling material burning rates can either be specified directly from experimental results, or alternatively, effective material pyrolysis properties can be established using numerical optimization algorithms, allowing the burning rate to vary locally with the magnitude of received radiation.

Approaching the fire engineering design of rapid transit systems from a risk based framework, coupled with CFD based flame spread modelling, allows for the likelihood and consequence of fire scenarios to be established and for the associated risk to be placed in context. This enables a pragmatic approach to fire safety design, as the effectiveness of various risk mitigation strategies can be evaluated, optimising the overall design.
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Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.

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ABSTRACT
Since energy storage systems represent key new technologies in the development of electric vehicles (EV), risks pertaining to them have to be examined closely. Lithium-ion (Li-ion) batteries powering EV contain highly energetic active materials and flammable organic electrolytes, which raise safety questions, different to conventional cars. In case of EV fire, concerns remain about batteries fire behavior, about their impact on the fire growth, about their fire-induced potential toxicity, especially in confined spaces and underground car parks and about their reaction with water in case of firemen intervention. Fire tests were therefore achieved for two French car manufacturers on two battery units, on a full battery pack, on an EV and on an analogous internal combustion engine (ICE) vehicle. Thermal and toxic threat parameters governing the fire risk were quantified. For this purpose, the heat release rate and the effective heat of combustion were determined to qualify the thermal impact whereas the main emitted gases governing the toxic potency of the fire effluents were measured. Fire consequences of an EV and the corresponding ICE vehicle were compared. This paper aims at presenting the main results of these fire tests.

KEYWORDS: electric vehicles, battery, fire, safety, experimental measurements.

INTRODUCTION
In 2005, the transport sector was responsible for approximately 15% of global greenhouse gas emissions, to which road transport contributes as high as 73% [1]. As part of emissions reduction policy, research devoted to alternative and decarbonated energy sources in substitution of fossil fuels in the transportation sector is crucial. In this field, making use of electric energy provided by a powerful battery is an innovative way. The high energy Li-ion battery is indeed one of the emerging new systems of electric storage [2][3][4] proposed in industries for innovative applications, in particular in the automotive sector (e.g. for Battery EV & plug-in EV), thanks to its high energy density.

Due to the reactivity of the materials and the high energy density involved, the Li-ion system may be subject to failures like thermal runaway leading to leakage, gas venting, fire and, in the worst case, explosion [5]. For this reason, more but still affordable safety precautions are needed: safety vent on each cell, fuses, battery and cell electrical management capable of single-cell supervision and control, etc. In general, most of the inherent hazards trigger accidental scenario when batteries are misused or facing abnormal environmental conditions. When operating out of the stability domain of the system (in terms of temperature or voltage), a series of undesirable reactions (varying according to the type of electrochemistry involved) may occur [6]. These side reactions can lead to the release of heat and gases, and then subsequently cause thermal runaway [7] that entails significant threats including fire phenomena or even explosion as a result of the combustion of the electrolyte and other combustible components after rupture of battery confinement.

External fire of Li-ion batteries and more globally of Li-ion powered EV represents a scenario likely to occur during battery or vehicle life. Indeed, in France, 60 832 ICE vehicle fires required assistance from the rescue services in 2011 [8].
To ensure the safe development of EV, French public authorities conducted different working groups with regard to EV safety management. To compensate a lack of technical knowledge on real EV fire behavior, the decision to proceed to EV full scale fire testing was taken with the aim of adjusting, as needed, some regulations, more particularly the ones regarding recharge station for EV in underground car parks or petrol stations. Public authorities led a group of experts, car manufacturers and emergency services to define an experimental procedure able to assess, in a suitable manner, the effects of EV fires and their consequences in confined spaces. The main objectives of this procedure were to characterize the general behavior of batteries and vehicles in case of external heat stress, to characterize batteries behavior in contact with water in case of firemen intervention, to identify and quantify emitted gases and energies and to compare fire growth. The defined protocol included five different tests on: two battery units (with and without fire fighting operation), one full battery pack, one EV and one analogous ICE vehicle. INERIS was commissioned to conduct these fire tests for two French car manufacturers in its fire gallery where many parameters were measured throughout the tests. This paper presents the main results and comparisons of the tests between an EV and the corresponding ICE car. A special attention was paid to the analysis of emitted gases, specifically toxic gases as HF and CO.

EXPERIMENTAL

Test procedure specifications

Full scale tests were achieved in the INERIS fire gallery, according to fire test procedure specifications developed by the EV safety group, which was mentioned above.

The procedure included five different tests:
- A fire test on a battery unit, a modular assembly of some elemental cells, which was a representative element of the full EV battery. (A battery unit represented at least ten percent of the full battery mass or its energy was at least 1.5 kWh.)
- A fire test on a battery unit, with fire fighting operation.
- A fire test on a full battery pack (which mass was around 250-300kg), with late fire fighting attempt.
- A fire test on an EV with a fully charged battery.
- A fire test on an analogous Diesel vehicle with a full gas tank.

In order to quantify emitted gases and energies, the tests had to be performed in a confined space which could be operated like a large-scale fire calorimeter.

The ventilation had to be slightly forced and monitored to fully extract combustion gases in the exhaust system and to carry out measurements.

The calibrated ignition source had to ensure a self-sustained fire of the tested elements. It was important to be able to stop the ignition source once the fire was self-sustained, in order to quantify the energy produced by the fire of the tested element without any external contribution of energy. The impact of the transitional ignition phase had to be minimised to get as accurate measurements as possible and not to interfere with emission of gases from the tested element. Therefore a 6 kW propane burner was used to set fire to the vehicles.

Testing facilities and equipments

These fire tests were achieved in the INERIS fire gallery. This gallery, schematized on Figure 1, is 50m long, 3.5m high (on the top of the vaulted ceiling), 3m wide (10 m² cross section), with a tower were the main sensors and samplers are set up. The tower is 2m long, 3m wide and 10m high. This gallery has a monitored ventilation system and a gas scrubber system which enables to canalize and clean up combustion smoke before rejection in the atmosphere.
Controlled conditions are generated in the fire gallery with the opportunity to analyze standard decomposition and combustion gases and therefore to quantify thermal and toxic parameters. The online gas analysis instrumentation, including a Fourier-Transform Infra-Red (FTIR) equipment, conjugated to flow rates measurements enable to determine the nature and yields of toxic combustion or decomposition products.

**Procedure dedicated to fire tests on vehicles**

For each car manufacturer, after preliminary tests on battery units and pack, a fire test was carried out on an EV and another test was carried out on an analogous ICE vehicle. In total, 4 large scale car fire tests were achieved with an identical experimental procedure.

The flow rate in the gallery was approximately 25 000m$^3$/h and it was measured throughout the fire tests. The ventilation system is an extraction one, which means that the fresh air gets in the gallery through the section under the door (section of 3m by 30cm) and it is extracted in the tower. For each test, the vehicle was set up in the tunnel of the fire gallery (Figure 1).

**Figure 1** Experimental set-up for the fire tests on a vehicle.

A gas burner of approximately 6 kW was used to set fire to the vehicle. To ensure a sustained fire of the vehicle, the left front seat had been lacerated and the car windows had been opened before the test. The gas burner was activated during 1 minute, orientated to the left front seat, inside the passenger cell.

Online gas analysis was performed by several methods:
- classical analytical methods using non-dispersive infra-red spectroscopy (NDIR) for CO$_2$ and CO, paramagnetic measurement for O$_2$, chemiluminescence for nitrogen oxides (NO$_x$) and flame ionization detector (FID) for total hydrocarbons (THC);
- a method based on an online Nicolet 6700 FTIR spectrometer, using a 2m gas cell of a volume of 200mL for further analysis of gases and vapors including HF, HCl, HBr, HCN, SO$_2$, CO, CO$_2$ and NO$_x$. The sampling probe and installation was set up to be compatible with the HF specificities, in the above mentioned operational conditions.


The other online measured parameters were:
- thermal flux with two fluxmeters located 5m and 8m upstream the vehicle,
- temperature inside and on the surface of the vehicle,
- smoke temperature,
- flow rate (smoke exhaust rate),
- video and thermal IR camera,
- online gas analysis (CO, CO₂, O₂, THC, NOₓ, HF, HCl, HBr, HCN, SO₂, etc.).

Off-line measurements and analysis were also carried out, including soot analysis and mass loss measurement.

The total effective heat of combustion and the fire growth were determined using the method of O₂ consumption.

**TEST RESULTS AND COMPARISON**

**Fire behavior and heat release rate (HRR)**

Fire development was found similar for all vehicles; the fire spread inside the passenger cell before propagating to the rear of the vehicle and then to the front of the vehicle. It’s worth noting however that fire propagation can be influenced by the ventilation imposed during the test and by the ignition method which is used.

The general behavior in case of an external fire initiating event was globally found similar for both types of vehicles. No explosion or projection related to the battery was observed during EV fire tests in our test conditions.

The measured mass loss was close for EV and ICE vehicles. For both car manufacturers, the measured mass loss was around 20% of the initial mass.

The maximal HRR and the overall dissipated effective heat of combustion (integration of HRR profile) were close for both analogous vehicles. The comparison of the evolution of HRR versus time for EV and ICE vehicle for the car manufacturer 1 and for the car manufacturer 2 are respectively represented in Figure 2 and Figure 3. In the present case, HRR computation is based on O₂ consumption corrected for CO and soot production. For the car manufacturer 1, the maximal HRR was 4.2 MW for the EV and 4.8 MW for ICE vehicle. Peaks attributed to the combustion of the battery pack appear at approximately 35 minutes after ignition. For the car manufacturer 2, the maximal HRR was 4.7 MW for the EV and 6.1 MW for ICE vehicle. Data of the literature mentioned that the HRR for a single passenger automobile (ICE vehicle) varies from 1.5 to 8 MW [11] [12] according to its size, but the majority of the tests reported in the literature show HRR values less than 5 MW [13] for medium size cars. Then, measured HRR values during our tests are consistent with data from literature.

The overall dissipated effective heat of combustion was computed at 6300 MJ for EV and 6900 MJ for ICE vehicle for the car manufacturer 1 (Figure 4) and at 8500 MJ for EV and 10000 MJ for ICE vehicle for the car manufacturer 2 (Figure 5). From these values, the effective heat of combustion expressed as heat of combustion (in MJ) per kg of combusted material was evaluated. The effective heat of combustion was around 36-36.5 MJ/kg for ICE vehicles of both manufacturers. This value is consistent with the plastic heats of combustion and with the effective heat of combustion of 35 MJ/kg reported in [13]. The effective heat of combustion was around 30-31 MJ/kg for electric vehicles of both car manufacturers.
Figure 2  Comparison of the heat release rate vs. time for EV and analogous ICE vehicle tests for the car manufacturer 1.

Figure 3  Comparison of the heat release rate vs. time for EV and analogous ICE vehicle tests for the car manufacturer 2.
Gas analysis

According to actual measurements, HF was emitted in significant quantities during both electric and ICE vehicles fire tests. This is shown in the graphs hereinafter, Figure 6 and Figure 7, representing mass flow of HF production as a function of time for both car manufacturers. It’s worth noting that a significant emission of HF was also measured during ICE vehicle tests. A similar peak of HF
emission at 14 min was observed for EV and ICE fire experiments. It may come from fluorinated materials contained in the vehicle (e.g. from a fluorinated refrigerant contained in the air conditioning system; this hypothesis wasn’t confirmed).

In the case of EV, additional HF emission peaks corresponding to the combustion of the lithium-ion battery pack were observed around 25-30 minutes after triggering vehicle fire, Figure 6 and Figure 7. This is consistent with known existing potential sources of fluorine in a Li-ion battery like the electrolyte (most often LiPF₆ in current technologies) and the binder material of the electrodes (often PVDF). This is also coherent with preliminary tests achieved on battery units and full battery pack. Consequently, HF cumulative mass was measured in higher quantities in the case of EV due to the combustion of Li-ion battery pack.

![Figure 6](image_url)

*Figure 6  Comparison of HF production vs. time for EV and analogous ICE vehicle tests for the car manufacturer 1*
As regards the other emitted gases, fire experiments showed the production of similar cumulative masses of CO₂, CO, THC, NOₓ, HCl and HCN for both types of vehicles. No HBr was detected for these 4 tests.

The total quantity of emitted gases (limited to measured gas and vapors) is reported in Table 1, in bold. This table doesn’t take into account the kinetic of gas emission, which is an important parameter.

The measured quantity of the main emitted gases (CO₂, CO, THC, etc.) and the thermal effects (HRR, heat of combustion) were higher for the manufacturer 2 due to the presence of a bigger amount of combustible material in its cars which are bigger models.
### Tested element

<table>
<thead>
<tr>
<th>Tested element</th>
<th>EV manufacturer 1</th>
<th>ICE vehicle manufacturer 1</th>
<th>EV manufacturer 2</th>
<th>ICE vehicle manufacturer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Voltage (V)</strong></td>
<td>330 V a</td>
<td>-</td>
<td>355 V a</td>
<td>-</td>
</tr>
<tr>
<td><strong>Capacity (Ah)</strong></td>
<td>50 Ah a</td>
<td>-</td>
<td>66,6 Ah a</td>
<td>-</td>
</tr>
<tr>
<td><strong>Energy (kWh)</strong></td>
<td>16,5 kWh a</td>
<td>-</td>
<td>23,5 kWh a</td>
<td>-</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>1 122 kg</td>
<td>1 128 kg</td>
<td>1 501 kg</td>
<td>1 404 kg</td>
</tr>
<tr>
<td><strong>Lost mass (kg)</strong></td>
<td>212 kg</td>
<td>192 kg</td>
<td>278,5 kg</td>
<td>275 kg</td>
</tr>
<tr>
<td><strong>Lost mass (%)</strong></td>
<td>19%</td>
<td>17%</td>
<td>18,6%</td>
<td>19,6%</td>
</tr>
</tbody>
</table>

### Online gas analysis – total quantity of emitted gases (FTIR and online analyzers)

<table>
<thead>
<tr>
<th>Gases</th>
<th>EV manufacturer 1</th>
<th>ICE vehicle manufacturer 1</th>
<th>EV manufacturer 2</th>
<th>ICE vehicle manufacturer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO₂(g)</strong></td>
<td>460 400</td>
<td>508 000</td>
<td>618 490</td>
<td>722 640</td>
</tr>
<tr>
<td><strong>CO₂ (mg/lost g)</strong></td>
<td>2 172</td>
<td>2 646</td>
<td>2 220,8</td>
<td>2 627,8</td>
</tr>
<tr>
<td><strong>CO (g)</strong></td>
<td>10 400</td>
<td>12 040</td>
<td>11 700</td>
<td>15 730</td>
</tr>
<tr>
<td><strong>CO (mg/lost g)</strong></td>
<td>49</td>
<td>63</td>
<td>42</td>
<td>57,2</td>
</tr>
<tr>
<td><strong>THC (g)</strong></td>
<td>2 430</td>
<td>2 380</td>
<td>2 860</td>
<td>2 730</td>
</tr>
<tr>
<td><strong>THC (mg/lost g)</strong></td>
<td>11,5</td>
<td>12,4</td>
<td>10,3</td>
<td>9,9</td>
</tr>
<tr>
<td><strong>NO (g)</strong></td>
<td>500</td>
<td>679</td>
<td>770</td>
<td>740</td>
</tr>
<tr>
<td><strong>NO (mg/lost g)</strong></td>
<td>2,4</td>
<td>3,5</td>
<td>2,8</td>
<td>2,7</td>
</tr>
<tr>
<td><strong>NO₂ (g)</strong></td>
<td>198</td>
<td>307</td>
<td>349</td>
<td>410</td>
</tr>
<tr>
<td><strong>NO₂ (mg/lost g)</strong></td>
<td>0,9</td>
<td>1,6</td>
<td>1,3</td>
<td>1,5</td>
</tr>
<tr>
<td><strong>HF (g)</strong></td>
<td>1 540</td>
<td>621</td>
<td>1 470</td>
<td>813</td>
</tr>
<tr>
<td><strong>HF (mg/lost g)</strong></td>
<td>7,3</td>
<td>3,2</td>
<td>5,3</td>
<td>3</td>
</tr>
<tr>
<td><strong>HCl (g)</strong></td>
<td>2 060</td>
<td>1 990</td>
<td>1 930</td>
<td>2 140</td>
</tr>
<tr>
<td><strong>HCl (mg/lost g)</strong></td>
<td>10</td>
<td>10,4</td>
<td>6,9</td>
<td>7,8</td>
</tr>
<tr>
<td><strong>HCN (g)</strong></td>
<td>113</td>
<td>167</td>
<td>148</td>
<td>178</td>
</tr>
<tr>
<td><strong>HCN (mg/lost g)</strong></td>
<td>0,5</td>
<td>0,9</td>
<td>0,5</td>
<td>0,6</td>
</tr>
</tbody>
</table>

### Thermal effects

<table>
<thead>
<tr>
<th>Thermal effects</th>
<th>EV manufacturer 1</th>
<th>ICE vehicle manufacturer 1</th>
<th>EV manufacturer 2</th>
<th>ICE vehicle manufacturer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximal HRR (MW)</strong></td>
<td>4,2 MW</td>
<td>4,8 MW</td>
<td>4,7 MW</td>
<td>6,1 MW</td>
</tr>
<tr>
<td><strong>Heat of combustion (MJ)</strong></td>
<td>6 314 MJ</td>
<td>6 890 MJ</td>
<td>8 540 MJ</td>
<td>10 000 MJ</td>
</tr>
<tr>
<td><strong>Heat of combustion/unit mass loss (MJ/kg)</strong></td>
<td>29,8 MJ/kg</td>
<td>35,9 MJ/kg</td>
<td>30,7 MJ/kg</td>
<td>36,4 MJ/kg</td>
</tr>
</tbody>
</table>

*a Characteristics of the battery pack of the EV.

### Table 1 Results synthesis

**CONCLUSION**

Four large scale fire tests were recently achieved, with an identical experimental procedure, for two French car manufacturers. For each of them, the fire testing program involved a) two battery units, b) a full battery pack, c) an EV and d) an analogous ICE vehicle. The present paper focused on the main results of the fire tests conducted on EV and corresponding ICE vehicles.

Our tests show that the general behavior of EV and ICE vehicles exposed to the same external heat stress was similar. The maximal heat release rate (HRR), the overall dissipated heat of combustion...
and the effective heat of combustion were close for both types of vehicles.

The analysis of the combustion gases from car fires highlighted that the cumulative masses of CO₂, CO, total hydrocarbons, NO, NO₂, HCl and HCN were similar for both types of vehicles. A significant quantity of HF was measured during EV and ICE vehicle fire tests. To our knowledge, HF emissions from conventional ICE vehicles have not been reported into the literature so far, may be due to recent introduction of fluorine sources in modern cars. The cumulative mass of HF was higher for EV due to the combustion of the Li-ion battery pack. In addition to HF, a significant quantity of toxic gases including CO and HCl, in relation with the presence of chlorinated polymers, was produced during the fire tests on both types of vehicles. All toxic compounds have to be examined to assess the global toxicity of combustion smokes during EV and ICE vehicle fires. These tests provided source terms, which can be used in modeling work to predict toxic gas dispersion and thermal effects in confined spaces, such as tunnels, underground car parks or other underground facilities.

The results of these tests are only valid for the four tested vehicles of two car manufacturers. Indeed, numerous parameters such as the fire scenario initiating event, the battery technology, its packaging, its design and its position within the vehicle are liable to play a significant role on the overall behavior of an EV exposed to an external fire. Thus, these results cannot be extrapolated to other vehicles, to other car manufacturers, to other potential fire scenarios or to other battery technologies.

These tests only studied the vehicle behavior in the case of a fire outbreak in passenger cell. In the case of a fire outbreak generated in the battery by an internal short circuit or an overcharge, the kinetics of observed phenomena would certainly be different.

**REFERENCE LIST**


Comparison of fire behaviors of an electric-battery-powered vehicle and gasoline-powered vehicle in a real-scale fire test

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ABSTRACT
The proportion of electric-battery-powered vehicle fires due to traffic accidents, electrical problems, arson and other causes will increase as the vehicles are further introduced into the market. There has been insufficient study to determine whether the burning of such a vehicle may present an unacceptable fire risk. To evaluate the fire risk for the battery-powered vehicle, flame propagation, the rate of heat release and radiation heat flux were obtained in real-scale fire tests of the vehicle and a gasoline-powered vehicle and compared. The Nissan Leaf (an electric-battery-powered vehicle) and Honda Fit (a gasoline-powered vehicle) were used in the tests. In the test of the battery-powered vehicle, there was no explosive burn of the lithium-ion rechargeable battery pack. The maximum magnitudes of the heat release rate and heat flux for the battery-powered vehicle were larger than those for the gasoline-powered vehicle. The fire risk for the battery-powered vehicle was higher than that for the gasoline-powered vehicle, but it was similar to that for a gasoline-powered luxury sedan. Our results provide useful information in determining risks associated with the burning of a battery-powered vehicle.

KEYWORDS: vehicle fire, fire risk, electric-battery-powered vehicle

1. INTRODUCTION
Electric vehicles are a transportation alternative with reduced environmental load. Electric vehicles powered by batteries are becoming more common in an effort to reduce CO₂ emissions. The Nissan Leaf is a typical electric vehicle on the market and has CO₂ emissions that are approximately 40% lower than the emissions of a comparable gasoline-powered vehicle according to life cycle assessment, as verified by the Japan Environmental Management Association for Industry, a public assessment institution (1).

A lithium-ion rechargeable battery (hereafter referred to as LiB) of large capacity is installed in the electric vehicle. The safety standards of the LiB are UL 1642 for the cell and UL 2054 for the battery pack in addition to IEC 61960. LiBs can be cylindrical, prismatic or laminated, and the electrolyte in a LiB is an organic compound that happens to be extremely flammable; e.g., dimethyl carbonate or diethyl carbonate. The exposure of a LiB to a fire will lead to an outburst and leakage of flammable gas from the LiB pack through a temperature rise of the electrolyte. Assessment of the fire risk posed by a LiB should clarify the effects of the outburst and the leakage on the spread of a fire. Because the overheating of the battery pack in a fire depends on the position of the battery pack in the vehicle, it is difficult to estimate the fire risk of a single battery pack in an electric vehicle.

The proportions of vehicle fires due to traffic accidents, electrical problems, arson and other causes may change with the introduction of electric vehicles into the marketplace. The fire behavior of vehicles has been studied to clarify the fire risk (2)-(4), but mainly only for gasoline-powered vehicles. The fire behavior of vehicles installed with LiBs of large capacity and no fuel tank will differ from
that of gasoline-powered vehicles. Additionally, the battery-powered vehicle has many special parts, and the burning of these parts will lead to fire behavior that differs from that of gasoline-powered vehicles. There has been insufficient study to determine whether the burning of a battery-powered vehicle will present an unacceptable fire risk. There is thus a need to better understand the fire behavior of the electric-powered vehicle.

The present study clarifies the fire risk for a vehicle in which a LiB pack was installed compared with that for a gasoline-powered vehicle. We examined flame propagation, the rate of heat release and the radiation heat flux in real-scale fire tests of a Nissan Leaf, which is an electric-battery-powered vehicle (hereafter referred to as the electric vehicle), and a Honda Fit, which is a gasoline-powered vehicle. These tests were performed by igniting a fully integrated soft rear bumper. In the test of the battery-powered vehicle, a flame was generated by the outburst of flammable gas, but there was no explosive destruction of the LiB pack. The results of the tests indicate that the fire risk for the Leaf was higher than that for the Fit. However, the fire risk for the Leaf was the same as that for luxury sedan vehicles that we obtained in a previous fire test.

2. EXPERIMENTAL

2.1. TEST VEHICLES

Figures 1 (a) and (b) show the vehicles used in the fire test: the Nissan Leaf and Honda Fit. These vehicles were five-door hatchbacks. The Leaf was equipped with four tires, and the Fit was equipped with four tires and a spare tire. Table 1 gives the specifications of the vehicles. The Leaf was somewhat larger than the Fit. The electric motor of the Leaf and the engine of the Fit were located at the front of the vehicles. The four side doors and the hood of the motor bay were made of aluminum in the Leaf and steel in the Fit.

Figure 2 shows the cell, module, and LiB pack for the Leaf. The battery pack was constructed from 48 modules each containing four cells and provided 360 V DC with 24 kWh capacity. Each cell was of laminated type, and the positive and negative electrodes, separator and electrolyte were sealed in the cell. The material of a positive electrode was a manganese-based alloy. The electrolyte was a flammable carbonic-acid-ester-based solvent. The battery pack had an upper shell and lower shell made of steel, and the shells sealed the module and harness. The battery pack was installed beneath the passenger compartment.

<table>
<thead>
<tr>
<th>Test vehicle</th>
<th>Model year</th>
<th>Drive powertrain layout</th>
<th>Dimensions</th>
<th>Gross weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Length</td>
<td>Width</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>2011</td>
<td>Front motor / front drive</td>
<td>4445 mm</td>
<td>1770 mm</td>
</tr>
<tr>
<td>Honda Fit</td>
<td>2003</td>
<td>Front engine / front drive</td>
<td>3830 mm</td>
<td>1670 mm</td>
</tr>
</tbody>
</table>

In the Fit, a plastic fuel tank was installed beneath the seats of the driver and front passenger. The fuel
filler lid was located on the left side of the vehicle at the rear.

2. 2. TEST CONDITIONS

Table 2 gives the test conditions of the vehicles. The LiB of the Leaf was fully charged. There was 10 L of gasoline in the fuel tank of the Fit. The windows of the four doors of the vehicles were closed. The electric motor or engine was shut off throughout the tests. In the tests, ignition was initiated at the fully integrated soft rear bumper of the Leaf and at the left-side soft rear splash guard of the Fit with 80 g of alcohol gel fuel. The vehicles were allowed to burn until the fires went out.

2. 3. MEASUREMENT

The tests were carried out in a fire test room (dimensions: 15 m (W) × 15 m (D) × 15 m (H)) with an electrostatic precipitator. We placed K-type thermocouples in the test vehicles to measure temperature, and used a video camera to obtain a video of the burning vehicle during the tests to observe the fire spread from the point of origin. As shown in Figure 3, each test vehicle was placed on a weighing platform, which was used to determine both the mass loss and the rate of mass loss of the burning vehicle. To estimate the total heat release and the heat release rate, we multiplied the combustion heat of a burning vehicle per unit weight (22 MJ/kg) by the mass loss and mass loss rate (3), respectively. The data of the temperature, mass loss and heat flux were stored in a recorder once

![Figure 2 Lithium-ion rechargeable battery installed in the Nissan Leaf.](image)

![Table 2 Test vehicle conditions](table)

<table>
<thead>
<tr>
<th>Test vehicle</th>
<th>Door windows</th>
<th>Amount of fuel in fuel tank</th>
<th>Charge ratio of LiB</th>
<th>Ignition location</th>
<th>Ignition source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissan Leaf</td>
<td>Closed</td>
<td>—</td>
<td>100%</td>
<td>Left-rear soft bumper</td>
<td>80 g of alcohol gel fuel</td>
</tr>
<tr>
<td>Honda Fit</td>
<td>Closed</td>
<td>10 L of gasoline</td>
<td>—</td>
<td>Left-rear splash guard</td>
<td>80 g of alcohol gel fuel</td>
</tr>
</tbody>
</table>

![Figure 3 Experimental configuration of the weighing platform used to measure the mass loss and the mass loss rate of the burning test vehicle.](image)
per second. The measurement accuracy of the weighing platform was 10 g. The vehicles were allowed to burn until the fires self-extinguished.

Figure 4 shows the locations of the heat-flux sensors in the surroundings of the test vehicle. We measured the heat flux at the front, right side and rear of the burning vehicle, with the heat flux sensors on the right side being set adjacent to the center pillar, rear tire and front tire. We set the distance \( d \) of the heat heat-flux sensors from the body surface to 0.5 and 1.0 m. We set the height \( h \) of the heat-flux sensors above the surface of the fire-resistant board of the weighing platform to 1.2 and 0.6 m for the front and rear sensors, 2.0 and 1.2 m for the center-pillar sensors and 0.3 m for the rear- and front-tire sensors.

![Figure 4 Experimental configuration of heat flux sensors around the test vehicle.](image)

3. RESULTS AND DISCUSSION

3. 1. ELECTRIC-BATTERY-POWERED VEHICLE

3. 1. 1. BURNING PROCESS

Figure 5 is a timetable of the burning of the electric vehicle. The duration of burning of each part was determined from the measured rise in temperature and the video of the burning vehicle. The bars show the range of the burning times for the luggage compartment, passenger compartment, motor bay and tires. A dot shows indicates the timing of an event.

The flame originating from the left-side soft rear bumper had propagated at near roof height along the body surface after about 9 min. Shortly afterward, the right- and left-rear tires and the luggage compartment began to burn, and a large flame formed at the rear. When the heat from the large flame that formed at the rear shattered the rear window about 20 min later, the rear flame grew and the door panels at the right and left rear subsequently melted. The melting of a door panel was slow, and there was no large opening of the panel in the short term. A flame that was presumed to be an outburst of flammable gas from the battery pack was observed from under the vehicle at about 37 min. The flame for this outburst lasted for about 1 min. When the heat from the flame that formed in the passenger compartment shattered the front window about 40 min later, the passenger compartment flame rapidly grew. The front door panels on the right and left began to melt with the rapid combustion of the passenger compartment, and the flame presumed to be the outburst of flammable gas relapsed under the vehicle for a few minutes. However, the battery pack did not burst or explode in this fire test.

Figure 6 shows the total voltage characteristic of the LiB for the electric-battery-powered vehicle. The total voltage of the LiB fell to almost 0 V at about 50 min.

The flame in the passenger compartment propagated to the motor bay through a through-hole in the fire wall and in the vicinity of the hinges of the front doors. The fall of the burning door mirror and
front fender inner panel led to the combustion of the right- and left-front tires, and the flame combined with the flame of the motor bay, which grew through the melting of the motor bay hood. The fire burned out completely about 120 min after ignition.

3.1.2. TOTAL HEAT RELEASE AND HEAT RELEASE RATE

Total heat release for the vehicle of 6.4 GJ was calculated from the experimental results for the mass loss. Figure 7 shows the curve of the heat release from the vehicle. The results are shown as a curve of the heat release rate calculated using the experimental values of the mass loss rate. There are two definite peaks in this curve: one after 9 min for the formation of the large flame through combustion of the rear, and one after 40 min for the formation of a combined large flame through combustion of the passenger compartment and the electrolyte. The peaks were 1.8 and 6.3 MW respectively. After the second peak, the heat release rate continued to exceed 3 MW for about 15 min.

![Figure 5 Burning process timetable of the electric-battery-powered vehicle.](image)

![Figure 6 Total voltage characteristic of the LiB for the electric-battery-powered vehicle.](image)
3.1.3. HEAT FLUX

Figure 8 shows curves of the heat flux in the surroundings of the vehicle. Figures 8 (a), (b), (c), and (d) are curves for the rear, right-side center pillar, front, and right-side front/rear tires respectively.

Figure 7 Heat release rate curve of the electric-battery-powered vehicle.

(a) Rear \((h = 1.2 \text{ m})\)

(b) Center pillar on right side \((h = 1.2 \text{ m})\)
Moreover, Figures 8 (a), (b), and (c) are for the case in which heat flux sensors are at a height of 1.2 m and Figure 8 (d) is for the case for a height of 0.3 m.

In Figure 8 (a), the maximum heat flux 0.5 m from the vehicle rear was 32 kW/m², corresponding to the large flame forming at the rear after 9 min. Subsequently, the heat flux decreased until it rose again to 27 kW/m² when the large flame of the passenger compartment and electrolyte formed after 40 min. In Figure 8 (b), the maximum heat flux 0.5 m from the center pillar was 51 kW/m², corresponding to the large flame that formed after 40 min. There was a combined flame of combustion of the passenger compartment and electrolyte after about 40 min, but heat flux of 50 kW/m² or more was obtained even after the size of the flame of the electrolyte decreased. Therefore, the curve of the heat flux in Figure 8 (b) might relate mainly to combustion of the passenger compartment. Additionally, at this distance, the heat flux continued to exceed 20 kW/m² for about 20 min. In Figure 8 (c), the maximum heat flux 0.5 m from the vehicle front was 40 kW/m², corresponding to the large flame that formed at the front after about 47 min. This value was obtained because the large flame in the motor bay was uncovered owing to the melting of the aluminum hood of the motor bay.

In the heat flux curve of Figure 8 (d), there are two definite peaks for the right-rear tire at a distance of 0.5 m. The peaks were 30 kW/m² at about 22 min and 62 kW/m² at about 41 min. We believe that the first peak relates mainly to the heat flux of the combustion of the right-rear tire because it was of the same magnitude as the only peak for the right-front tire. We believe that the second peak mainly

![Figure 8](image_url)
relates to the combustion of the electrolyte because of the timing and the height of the sensor. This result indicates that the fire risk relating to the flame of the outburst of the electrolyte is at a low position of the vehicle.

3.2. GASOLINE-POWERED VEHICLE

3.2.1. BURNING PROCESS

Figure 9 is a timetable of the burning of the gasoline-powered vehicle. The bars for the luggage compartment, passenger compartment, motor bay and tires show the duration of the burning. The flame originating at the left-side soft rear bumper had propagated at near roof height along the body surface about 14 min after the test began. Afterward, the burning of the right- and left-rear tires and the luggage compartment started, and the gasoline vapor that leaked from the fuel filler cap formed a flame in the vicinity of the fuel filler lid. A large flame at the rear formed from these flames, and the shattering of the left-rear fixed window and the rear window by the heat increased the combustion of the luggage compartment. When the heat from the flame that formed in the passenger compartment shattered the front window after about 35 min, the passenger-compartment flame rapidly grew. Gasoline did not leak from the tank when the fuel tank combusted. We believe that the gasoline was heated before the combustion of the tank and became a vapor, and it had thus already leaked from the tank through the fuel filler pipe.

![Figure 9 Burning process timetable of the gasoline-powered vehicle.](image)

![Figure 10 Heat release rate curve of the gasoline-powered vehicle.](image)
The flame in the passenger compartment propagated to the engine bay through a through-hole in the fire wall and in the vicinity of hinges of the front doors. The fall of the burning door mirror and inner cover of the front fender led to the combustion of the right- and left-front tires, and the flame combined with the flame of the motor bay that grew through the melting of the engine bay hood. The fire burned out completely about 120 min after ignition. There was a difference in the fire behavior between the gasoline and electrolyte, but the process of the flame propagating to the luggage compartment, passenger compartment and engine bay was the same for the gasoline-powered vehicle and electric vehicle.

3.2.2. TOTAL HEAT RELEASE AND HEAT RELEASE RATE

The total heat release for the vehicle was 4.3 GJ. Therefore, the mass of the inflammables in the gasoline-powered vehicle was less than that in the electric vehicle. In a previous fire test of gasoline-powered vehicles, we obtained total heat release of 7.4 GJ for a Toyota luxury sedan, 5.9 GJ for a Toyota minivan, 5.3 GJ for a Nissan minivan, 5.6 GJ for a Subaru station wagon and 5.1 GJ for a Toyota sedan. These results indicate that the total heat release for the electric vehicle was similar to that for a general gasoline-powered vehicle. In these tests, the amount of gasoline in the fuel tank was 10 L.

Figure 10 shows the curve of the heat release from the vehicle. The peaks were not sharp like those for the electric vehicle although there were two peaks: one after 35 min for the formation of the large

![Figure 10](image_url)

(a) Rear (h = 1.2 m)

(b) Center pillar on right side (h = 1.2 m)
flame through combustion of the passenger compartment, and one after 53 min for the formation of
the large flame through combustion of the engine bay. The peaks were 2.1 and 2.0 MW respectively.
After the first peak, the heat release rate continued to exceed 1.8 MW for about 20 min.

3. 2. 3. HEAT FLUX

Figure 11 shows the curve of the heat flux of the vehicle surroundings. Figures 11 (a), (b), (c), and (d)
show the curves for the rear, right-side center pillar, front and right-side front/rear tires respectively.
Moreover, Figures 11 (a), (b), and (c) are for the heat flux sensors at a height of 1.2 m and Figure 11
(d) is the case for a height of 0.3 m.
In Figure 11 (a), the maximum heat flux 0.5 m from the rear was 23 kW/m², corresponding to the
large flame that formed at the rear after 32 min. The maximum value was about 70% of that for the
electric vehicle. Because the shapes of the two vehicles were almost the same, we considered that
there was less inflammables in the vicinity of the rear including the luggage compartment for the
gasoline-powered vehicle than for the electric vehicle. In Figure 11 (b), the maximum heat flux 0.5 m
from the center pillar was 40 kW/m² or more, corresponding to the large flame that formed after 38
min. The heat flux continued to exceed 20 kW/m² for about 10 min at this distance. In Figure 11 (c),
the maximum heat flux 0.5 m from the front was 31 kW/m², corresponding to the large flame that
formed at the front after 52 min. Because the combustion of the engine bay had been covered by the engine hood, this heat flux for the gasoline-powered vehicle was about 20% less than that for the electric vehicle. In the heat flux curve of Figure 11 (d), the peaks in the heat fluxes at the rear and front tires almost coincided. The peaks 0.5 m from the rear tire and front tire were 30 and 26 kW/m² respectively. These values were almost the same as those for the electric vehicle. We estimated that the heat release rate of the tire was independent of the shape of the vehicle. The fire test showed that the heat fluxes 0.5 and 1.0 m from the cars were smaller for the gasoline-powered vehicle than for the electric vehicle in general. This result is due to there being less combustible material in the gasoline-powered vehicle than in the electric vehicle. Additionally, the melting of the door panels and the hood of the motor bay in the electric vehicle might have affected this result. It is also believed that a localized effect of the outburst of the electrolyte in the vicinity of the vehicle bottom would have affected this result.

CONCLUSIONS

To evaluate the fire risk posed by a battery-powered vehicle, this study determined flame propagation, the rate of heat release and the radiation heat flux of a battery-powered vehicle and a gasoline-powered vehicle in real-scale fire tests and compared the results. In the test of the battery-powered vehicle, there was no explosive burn of the LiB pack. The maximum magnitudes of the heat release rate and heat flux for the battery-powered vehicle were larger than those for the gasoline-powered vehicle. The fire risk posed by the battery-powered vehicle was higher than that posed by the gasoline-powered vehicle, but it was at a level similar to that posed by a gasoline-powered luxury sedan.

REFERENCE LIST


National Electric/Hybrid Vehicle Training Programs for First Responders

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Quincy, USA

ABSTRACT

The National Fire Protection Association (NFPA) has been working on a three year project, funded by the Department of Energy and NFPA, to develop and deliver Electric/Hybrid Vehicle Safety Training to U.S. Emergency Responders, in order to prepare them for their role in safely handling incidents involving Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV), Electric Vehicles (EV), and the charging station equipment. A 4 hour classroom training course was developed for the fire service, which consists of a pre- and post-test, PowerPoint slides, a student manual, videos, computer animations, and a quick reference Emergency Field Guide for on-scene instruction. An 8 hour Train-the-Trainer course has also been developed, providing the framework and additional course materials to enable instructors to teach the course effectively through their respective state training systems. This program is currently being delivered to fire service trainers in all 50 U.S. states. A newly created website (www.EVsafetytraining.org) serves as a central repository for all U.S. Emergency Responders, where NFPA and their partners, including the automobile manufacturers, now host all pertinent Electric/Hybrid vehicle safety information, Emergency Response Guides, a calendar of events, videos, blogs and additional training materials. A self paced e-learning program has also been developed in order to broaden the training’s reach, especially within our volunteer fire service. NFPA also recently released their Electric Vehicle Emergency Field Guide, which serves as a database of key technical safety information on electric/hybrid vehicles currently on the road, and is available both electronically and in print, to be used as a quick reference guide at electric/hybrid incidents. Classroom versions of our Electric Vehicle Safety Training are currently being developed for Law Enforcement and EMS, and will be released later this year.

KEYWORDS:

electric vehicles, EV, hybrid vehicles, HEV, plug in hybrid vehicles, PHEV, EVSE, charging stations, safety, training, emergency response, first responder

INTRODUCTION

To address the federal government’s goal of putting one million advanced electric drive vehicles on our nation’s roadways by 2015, and to address the safety aspect of the more than 2 million hybrid vehicles currently in use, the Department of Energy (DOE) funded a comprehensive series of programs to develop EV technology and education that will enable the safe introduction of advanced electric drive vehicles to the marketplace, as well as provide continued development and education on the advancement and safety of the existing hybrids on our roads today. This paper will describe and illustrate the nationwide training program that the National Fire Protection Association (NFPA) has developed as a recipient of one of these DOE grants, in order to help prepare first response personnel to more safely address crashes involving hybrid and electric vehicles. The National Fire Protection
Association is the ANSI accredited developer of codes and standards for first responder safety and facility fire, as well as electrical safety, which includes the National Electrical Code®. NFPA has the existing codes and standards infrastructure, the recognized training infrastructure and the relationships with the emergency responder communities and auto manufacturers required to make EV/HEV safety training practical and accessible for our nation’s emergency responders.

BACKGROUND

For many years, NFPA has been aware of the safety issues that the new technologies found in hybrid and electric vehicles may pose to first responders. As a result, NFPA applied for and received a grant from the Department of Energy to develop and deliver a training curriculum on Electric and Hybrid Vehicle Safety for First Responders. This program presents emergency first responders with the training and reference materials necessary to respond to emergency situations involving all hybrid and electric vehicles on our nation’s roads. The online distance learning and classroom train-the-trainer program provides information on how to identify EVs, their electrical and safety systems, immobilization procedures, manufacturer recommended power down procedures, extrication awareness (with respect to high voltage cables and high strength steel) and recommended practices when dealing with emergency situations, including submersion and battery fires. It also discusses the new challenges presented by vehicle charging stations and their infrastructure.

This program is currently being delivered to members of the fire service across the nation, and classroom training is under development for the law enforcement community. This professional training program was developed using extensive research findings from NFPA, the Fire Protection Research Foundation, EV Subject Matter Experts and nationwide first responder focus groups and surveys.

METHODOLOGY

The first step in this developing this project was to form an Emergency Responder Technical Panel, which consists of representatives from all of the major U.S. fire organizations, major law enforcement organizations and towing service associations. As shown in Figure 1, the Emergency Responder Technical Panel helped determine and identify potential hazards presented by electric vehicles, which subsequently steered the curriculum development process. This panel meets with NFPA twice a year and continues to provide guidance on the training needs and delivery strategies for this effort.
NFPA then formed partnerships with the major automobile manufacturers (17 to date), who provide technical source information and safety guidance on best emergency practices for the different makes and models of vehicles in production. With the automakers’ permission, this continually updated information is used in NFPA’s coursework, as well as our reference materials. Ford, GM, Nissan, BMW, Mitsubishi, VW, Toyota, Porsche, Honda, Lexus, Mercedes-Benz, Hyundai, Kia, Fisker, Coda, Alt-e, and Tesla have partnered with NFPA and offered support to help make NFPA’s website the central reference location for all U.S. Emergency Responders.

A communications/public relations firm was then hired to develop and execute a nationwide EV safety media campaign, both in trade magazines, the press and the web. To date, there have been over 500 million earned media impressions from this effort.

NFPA then conducted 17 focus groups across the country, consisting of groups of first responders being asked two hours of questions about EVs and training specifics. Then, an additional 425 phone surveys were conducted, targeted directly at fire service trainers in U.S. cities where the EV vehicles are being sold. All of the responses to these qualitative and quantitative studies has been collected and used to determine the content and materials developed and the venues to hold such trainings.

Next, ten subject matter experts in electric vehicles, extrication and/or fire extinguishment were hired, and the content for the curricula was developed by these SMEs and our NFPA staff based upon the emergency scenarios displayed in Figure 2.

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*Figure 1  Potential hazards*
As the next step, a training curriculum organization was hired to take our content and produce engaging classroom training programs. As a result, a fire service train-the-trainer course, an instructor-led classroom course, self-paced e-learning modules, animations, simulations and videos were produced, which offer an engaging and interactive learning approach. As these trainings were developed, they were reviewed by NFPA’s Public Fire Protection and Electrical Divisions to assure alignment with NFPA codes and standards. Videos and animations ranging from identifying EVs, basic electrical concepts and battery types, to fire response principles have been produced by this organization and are an integral part of the training.

As the training programs were released, a distribution plan was devised and is now underway as NFPA partners with the fire service directors in each state to outline where each course will be held and which fire service trainers will participate. As our train-the-trainer courses are being offered to each state, participating trainers in that state will then continue to propagate the course as they train their peers throughout their respective geographic regions. In order to propagate the classroom training nationwide and reach the highest number of responders, NFPA has partnered with North American Fire Training Director Association (NAFTD) representative in each state to identify the venue for the training class and involve the appropriate people in that state. Thus far, we have delivered the training to 2100 fire service trainers across 34 states. Our goal is to train fire service training in every state by the first quarter of 2013. Each trainer who attends an NFPA train-the-trainer session receives all the course materials needed to deliver the course throughout the rest of their state’s training networks and departments, as well as a copy of NFPA’s Emergency Field Guide. Those trainers have now subsequently trained over 10,000 additional members of the U.S. fire service, as the propagation of the education continues. As of the summer of 2012, NFPA’s various first responder EV safety training programs have reach an audience of over 30,000 U.S. first responders.
NFPA’s EV web portal, www.EVsafetytraining.org, was also constructed and is live, as it serves as the central repository for all U.S. EV safety information. It hosts training, videos, simulations, events, a calendar, blogs, news stories, and a separate area for each auto manufacturer to provide their own safety information to responders, including their emergency response guides, safety brochures, documents, presentations and videos. Our website received over 135,000 visits since its release, truly making it the ‘go to’ source for our nation’s responders. Our EV Safety Training Blog, which is written by NFPA’s staff and SMEs, has received over 36,000 hits to date. Additionally, NFPA now publishes and distributes a monthly EV Safety Newsletter, which has over 22,500 subscribers.

In 2011, General Motors turned over all of their EV Safety Training programs to the NFPA. In response, NFPA developed and hosts an online Chevy Volt safety training course as the first in a series of online trainings. This online course can be found on NFPA’s web portal, and to date has had over 17,500 responders participate.

More recently, a quick reference guide called NFPA’s Emergency Field Guide (EFG) was developed that contains vital vehicle safety information for an Emergency Responder on the scene of a crash on how to identify, immobilize and disable current production models of hybrid and electric vehicles. The EFG was developed at the request of first responders who participated in our initial market research project. Their feedback made it evident that it is often difficult to find, download and read each manufacturer’s hybrid/electric Emergency Response Guides for every vehicle make and model, often containing 15-30 pages each. This new quick reference guide now provides first responders with life-saving information for on-scene reference in a concise, consistently formatted manner, which has been technically reviewed by each manufacturer and NFPA. When responders are at the scene of an incident involving a hybrid/electric, they now have the essential safety information in an easy-to-use, indexed, and conveniently designed layout, which includes descriptions, diagrams, locations of key high voltage electric components, vehicle power down techniques and emergency procedures, including battery fire extinguishment, charging station incidents and vehicle submersion. This print manual is being provided to each student who attends a train-the-trainer session and is available for purchase on NFPA’s websites. This EFG is also available electronically as a fully linked PDF, and will be made available as a web based application later this year.

Our most recent project milestone was the release of our 2 hour online self-paced study program. This dynamic online course, which covers the same topics and material as addressed in our classroom training program, provides the user with a condensed, interactive learning experience, filled with videos, animations, review quizzes and simulations that provide opportunities to put learned information into practice. These scenarios include fire, submersion, unresponsive drivers and crashes involving charging stations, and the system allows the student to review whatever section of the material he/she wishes as many times as they wish. Data review questions are presented after each module and must be answered correctly before the next module can be started, and scenario room final exams are given at the end of the course, before the student receives an NFPA certificate and CEU credit.

**NEXT STEPS**

This year, NFPA signed an agreement with a major State Police Organization to co-develop a state of the art Law Enforcement EV classroom training program. The International Association of Chiefs of Police’s (IACP) Highway Safety Committee and the National Sheriffs Association’s (NSA) Highway Safety Committee both unanimously passed a resolution of support for NFPA’s Law Enforcement training. This training, which will include a crash and reconstruction safety module, will be released in the fourth quarter of 2012.

As hybrid and electric vehicles sales continue to increase, it is critical that both first responders and the general public be educated on hybrid/electric vehicle safety. NFPA is leading that effort, providing electric and hybrid vehicle safety information, training and reference material to Emergency
Responders nationwide. For more information on this project, please visit our Electric Vehicle Safety Training website: www.EVSafetyTraining.org.
Determining Hydrogen Concentration in a Vehicle after a Collision Test

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ABSTRACT
We conducted an in-vehicle hydrogen leak test in a simulated post-side-crash condition to develop a hydrogen leak test method in enclosed spaces after collision testing. Hydrogen gas was released from three positions under the vehicle floor and one position inside the cabin at various flow rates not exceeding the allowable post-crash limit of 118 NL/min. The test results indicated that at a flow rate of 69 NL/min (half the allowable post-crash limit) the hydrogen concentration in the vehicle rose above 4% in some cases; that the hydrogen concentration decreased with the reduction of leakage nozzle diameter when the leakage position and the flow rate were kept constant; that the hydrogen concentration was varied by winds, suggesting the need to specify wind conditions for hydrogen leak tests.

KEYWORDS: hydrogen, vehicles, leak, post-crash test

1. INTRODUCTION
While drafting of the UN Global Technical Regulation on the Safety of Hydrogen Fuel Cell Vehicles is in progress, discussion is underway on the Post-Crash Test of Enclosed Spaces – Compressed Hydrogen Storage [1]. In this prospective test, hydrogen concentrations will be measured at various points in the vehicle which has undergone a collision test. However, it is still unknown as to how much hydrogen will infiltrate into the vehicle cabin in a post-crash test condition where one or more vehicle windows may be broken open by crash impact. Additionally there are possible influences of winds on in-cabin hydrogen concentrations in testing facilities especially in outdoor testing grounds.

This test, simulating a post-side-crash test condition and assuming hydrogen leakages at flow rates below the allowable post-crash limit of 118 NL/min, was undertaken to determine hydrogen concentrations inside the vehicle and to investigate the effect of winds on the hydrogen concentration in order to develop a post-crash hydrogen leak test method for hydrogen-fueled vehicles.

2. TEST METHOD
2.1 Test vehicle
Employed as the test vehicle was a gasoline-fueled station wagon whose central side window was kept open to simulate a window broken in a side collision test. Only simulating a post-crash condition, the test vehicle did not undergo an actual collision test. It was confirmed before the test that the exhaust air duct of the vehicle cabin was normally functioning so that there would be no rapid surge of air pressure inside the cabin by the shutting of a door or by ventilation failure.

2.2 Test condition
The following six parameters were varied in the measurement of hydrogen concentrations at multiple measurement positions in the test vehicle: 1) hydrogen leakage position, 2) leakage direction, 3) leakage nozzle diameter, 4) leakage flow rate, 5) ambient wind, 6) leakage duration.

a) Hydrogen leakage position
Figure 1 shows the hydrogen leakage positions for the test vehicle.
Hydrogen was released at various flow rates controlled by a mass flow-meter at the following four leakage positions (A) to (D):

**<Under the vehicle floor>**
- (A) center position under the floor
- (B) opened window side under the floor
- (C) center position under the rear floor

**<In the cabin>**
- (D) center position on the rear seat floor

**b) Hydrogen leakage direction**
Two leakage directions were applied: (U) upward, (D) downward.

**c) Leakage nozzle diameter**
Three different nozzle diameters were applied: φ1, 2 and 4 mm.

**d) Hydrogen flow rate**
Three hydrogen flow rates were used: 118 NL/min (allowable limit in collision tests), 69 NL/min (half of the allowable limit), and 35 NL/min (quarter of the allowable limit).

**e) Ambient wind**
A blower was used to generate winds. The appearance and location of the blower are shown in Figure 2.
The blower with a fan diameter of 600 mm was placed 3m away from the opened widow vehicle side and was set to generate winds at a rate of 65 m³/min (average wind velocity of 3.59 m/s), which resulted in an average wind velocity of 0.5 m/s as measured at the opened central window.

f) Leakage duration
Two durations of hydrogen leakage was applied: 800 sec which was the time required for hydrogen concentrations inside the cabin to stabilize, and 30 sec which was the time for the hydrogen remaining inside the fuel duct to leak at a flow rate of 118 NL/min (assuming the cubic content of the duct to be 59L).

The abbreviated terms listed in Table 1 may be used hereafter in this report to indicate the test conditions explained in section 2.2.

<table>
<thead>
<tr>
<th>Leak Positions</th>
<th>Direction</th>
<th>Nozzle Dia. [mm]</th>
<th>Flow rate [NL/min.]</th>
<th>Wind</th>
<th>Leak time [sec.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>□ □ □ □ □ □ □</td>
<td>□ U: Upper</td>
<td>□ 1</td>
<td>□ 118</td>
<td>□ N: No</td>
<td>□ (None): 800sec.</td>
</tr>
<tr>
<td>□ □ □ □ □ □ □</td>
<td>□ D: Downward</td>
<td>□ 2</td>
<td>□ 69</td>
<td>□ Y: Yes</td>
<td>□ 30s: 30sec.</td>
</tr>
<tr>
<td>□ □ □ □ □ □ □</td>
<td>□ C: The central position under the rear floor</td>
<td>□ 4</td>
<td>□ 35</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>□ □ □ □ □ □ □</td>
<td>□ B: The opened window side under the vehicle floor</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

Ex) AU4-69N
Leak position : The central position under the vehicle floor, Direction: Upper, Leakage nozzle diameter = φ 4mm, Flow rate = 69NL/min, Wind : None, Leak time = 800 second

2.3 Measurement of hydrogen concentration
Thermal conductivity hydrogen sensors (New Cosmos Electric Co., Ltd. XP-314) were placed at the five different positions shown in Figure 3 for the measurement of hydrogen concentrations inside the cabin.
Additional thermal conductivity hydrogen sensors were installed at four measurement positions around the opened central window in order to determine the infiltration and escape routes of released hydrogen (Figure 4).
3. RESULTS AND DISCUSSION

3.1 Behavior of leakage hydrogen

Figure 5 shows the measured values of hydrogen concentrations in relation to time as hydrogen was released from the center position under the vehicle floor at a flow rate of 118 NL/min.

![Graph showing hydrogen concentration over time](image1)

It was found that hydrogen, after release from under the vehicle floor, moved up around the vehicle body from such areas as the rear tire housing (C9) and vehicle underbody (C8) and that some of the hydrogen infiltrated into the cabin from the opened window; thus hydrogen concentrations near the roof (C1~C4) gradually increased inside the cabin, finally stabilizing at about 800 sec onwards.

3.2 Effect of nozzle diameters (leakage velocity)

Figures 6 and 7 show the measured values of hydrogen concentrations in relation to time as hydrogen was released upward at a flow rate of 118 NL/min from two different leak positions: positions C and D respectively. Table 2 shows the maximum hydrogen concentrations at measurement positions C1~C5 in relation to time when the flow rate (118 NL/min), leak position and direction were kept constant while only the nozzle diameter was varied.

Of the five measurement positions in the cabin, C3 (center of the vehicle roof) registered the highest hydrogen concentration. This was reasoned that since C3 was located above the upper end of the opened central window, infiltrating hydrogen gathered around C3 instead of escaping from the open window.

Regarding the effects of different nozzle diameters while the leak position and direction were constant, the maximum hydrogen concentrations in the cabin rose with the increase of the diameter. This was explained that as the nozzle diameter increased at a constant flow rate, the hydrogen flow speed was...
reduced so that the hydrogen became less likely to get stirred and mixed with ambient air [2].

Table 2 Maximum Hydrogen Concentrations with Varied Nozzle Diameters

<table>
<thead>
<tr>
<th>Test name</th>
<th>Leakage position</th>
<th>Direction</th>
<th>Nozzle Diam. [mm]</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>Max C1~C5</th>
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</thead>
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<td>4</td>
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</table>

3.3 Effect of leakage flow rates and positions

Table 3 shows the maximum values of hydrogen concentrations when the leak position, direction and flow rate were varied while the nozzle diameter was kept constant at 4 mm.

Table 3 Maximum Hydrogen Concentrations with a Constant Nozzle Diameter

<table>
<thead>
<tr>
<th>Test name</th>
<th>Leakage position</th>
<th>Direction</th>
<th>Flow rate [NL/min]</th>
<th>C1</th>
<th>C2</th>
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<th>C5</th>
<th>Max C1~C5</th>
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<td>2.37</td>
<td>2.06</td>
<td>3.85</td>
<td>2.99</td>
<td>0.19</td>
<td>3.85</td>
</tr>
<tr>
<td>DU4-118N</td>
<td>D</td>
<td>Upper</td>
<td>118</td>
<td>5.23</td>
<td>5.12</td>
<td>7.37</td>
<td>5.06</td>
<td>0.30</td>
<td>5.95</td>
</tr>
<tr>
<td>DU4-69N</td>
<td>D</td>
<td>Upper</td>
<td>69</td>
<td>4.15</td>
<td>4.03</td>
<td>5.95</td>
<td>5.06</td>
<td>0.30</td>
<td>5.95</td>
</tr>
<tr>
<td>DU4-35N</td>
<td>D</td>
<td>Upper</td>
<td>35</td>
<td>2.72</td>
<td>2.65</td>
<td>4.25</td>
<td>3.49</td>
<td>0.25</td>
<td>4.25</td>
</tr>
</tbody>
</table>

3.3.1 Leakage flow rate

As shown in Table 3, when the leakage position and direction were kept constant, there was a tendency of the hydrogen concentrations in the cabin to go up with the increase of the leakage flow rate.

3.3.2 Leakage position

The maximum values of hydrogen concentrations in the cabin exceeded 4% when hydrogen was released upward from central rear underfloor position C at a flow rate of 69 NL/min or more. The only condition in which the maximum hydrogen concentrations registered at no more than 2% was...
the release of hydrogen from central underfloor position A at a flow rate of 35 NL/min. Comparisons of leakage positions A, B and C indicated that the highest maximum hydrogen concentration was recorded with rear underfloor position C, and Figure 6 shows changes in the maximum hydrogen concentration in time for the case of hydrogen release from leakage position C.

The test results suggested that some of the hydrogen released from rear underfloor position C passed measurement position C9 above the tire housing and entered into the cabin from the lower part (C7) of the opened window and that the infiltrated hydrogen diffused along the longitudinal directions of the vehicle roof before some of the saturated hydrogen escaped from the upper part of the opened window (C6).

On the other hand when hydrogen was released upward from in-cabin rear-seat floor position D, the maximum values of hydrogen concentrations inside the cabin exceeded 4% even though the leakage flow rate was the lowest at 35 NL/min. Figure 7 shows the maximum hydrogen concentrations in time with hydrogen released upward from the above-mentioned position D at a flow rate of 118 NL/min.
The hydrogen released from in-cabin central rear-seat floor position D was detected in the highest concentration and at the earliest time at measurement position C3 in the vehicle roof center. It was also found that the hydrogen saturated inside the cabin escaped from the upper part (C6) of the opened window.

3.4 Effect of leakage time

Table 4 shows the maximum values of hydrogen concentrations measured 30 sec and 800 sec after the release of hydrogen.

<table>
<thead>
<tr>
<th>TESTname</th>
<th>Leakage time [sec]</th>
<th>Leakage position</th>
<th>Direction</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>Max C1–C5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4–118N30s</td>
<td>30</td>
<td>A</td>
<td>Upper</td>
<td>0.39</td>
<td>0.17</td>
<td>0.34</td>
<td>0.24</td>
<td>0.18</td>
<td>0.39</td>
</tr>
<tr>
<td>A4–118N</td>
<td>800</td>
<td>A</td>
<td>Upper</td>
<td>2.61</td>
<td>1.68</td>
<td>2.78</td>
<td>2.38</td>
<td>0.40</td>
<td>2.78</td>
</tr>
<tr>
<td>A4–118N30s</td>
<td>30</td>
<td>A</td>
<td>Downward</td>
<td>0.56</td>
<td>0.28</td>
<td>0.55</td>
<td>0.32</td>
<td>0.18</td>
<td>0.56</td>
</tr>
<tr>
<td>A4–118N</td>
<td>800</td>
<td>A</td>
<td>Downward</td>
<td>2.45</td>
<td>1.95</td>
<td>3.03</td>
<td>2.56</td>
<td>0.44</td>
<td>3.03</td>
</tr>
<tr>
<td>B4–118N30s</td>
<td>30</td>
<td>B</td>
<td>Upper</td>
<td>0.78</td>
<td>0.65</td>
<td>1.74</td>
<td>1.27</td>
<td>0.17</td>
<td>1.74</td>
</tr>
<tr>
<td>B4–118N</td>
<td>800</td>
<td>B</td>
<td>Upper</td>
<td>2.62</td>
<td>3.02</td>
<td>3.55</td>
<td>3.43</td>
<td>0.30</td>
<td>3.55</td>
</tr>
<tr>
<td>B4–118N30s</td>
<td>30</td>
<td>B</td>
<td>Downward</td>
<td>0.38</td>
<td>0.19</td>
<td>0.65</td>
<td>0.28</td>
<td>0.17</td>
<td>0.65</td>
</tr>
<tr>
<td>B4–118N</td>
<td>800</td>
<td>B</td>
<td>Downward</td>
<td>2.53</td>
<td>2.29</td>
<td>2.99</td>
<td>2.83</td>
<td>0.76</td>
<td>2.99</td>
</tr>
<tr>
<td>C4–118N30s</td>
<td>30</td>
<td>C</td>
<td>Upper</td>
<td>1.08</td>
<td>0.49</td>
<td>1.46</td>
<td>0.83</td>
<td>0.16</td>
<td>1.46</td>
</tr>
<tr>
<td>C4–118N</td>
<td>800</td>
<td>C</td>
<td>Upper</td>
<td>3.66</td>
<td>2.37</td>
<td>4.69</td>
<td>3.75</td>
<td>0.20</td>
<td>4.69</td>
</tr>
</tbody>
</table>

The results indicated that maximum hydrogen concentrations in the cabin would not exceed 2% even
if the entire quantity of hydrogen remaining in the fuel duct was to leak out.

3.5 Effect of Wind

If a collision test is carried out in an outdoor testing ground, hydrogen concentrations inside the cabin may be affected by winds. Consequently the effect of winds was tested by using a blower directed towards the opened window of the test vehicle. Figure 8 shows the measured hydrogen concentrations when hydrogen was released from central underfloor position A, while the blower was operated from time 600 sec.

As soon as the opened window of the test vehicles received a 0.5m wind starting from time 600 sec, the hydrogen concentrations diminished presumably because the wind had an effect of reducing hydrogen infiltration into the cabin. On the other hand, Figure 9 shows the measurement results with hydrogen released from an in-cabin point (position D) and the blower in operation from time 900 sec to 1,200 sec. Table 5 compares the effects of the absence and presence of winds on the maximum hydrogen concentrations when hydrogen was released from in-cabin position D.
Table 5  Maximum Hydrogen Concentrations with Leakage Position D and Wind Absent/Present

<table>
<thead>
<tr>
<th>TESTname</th>
<th>Wind</th>
<th>Flow rate [NL/min.]</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DU4-118N</td>
<td>No</td>
<td>118</td>
<td>5.19</td>
<td>5.05</td>
<td>7.37</td>
<td>0.11</td>
<td>6.30</td>
</tr>
<tr>
<td>DU4-118Y</td>
<td>Yes</td>
<td>118</td>
<td>8.26</td>
<td>8.31</td>
<td>10.35</td>
<td>0.15</td>
<td>8.63</td>
</tr>
<tr>
<td>DU4-69N</td>
<td>No</td>
<td>69</td>
<td>4.15</td>
<td>4.03</td>
<td>5.95</td>
<td>5.06</td>
<td>0.30</td>
</tr>
<tr>
<td>DU4-69Y</td>
<td>Yes</td>
<td>69</td>
<td>5.71</td>
<td>5.70</td>
<td>7.67</td>
<td>6.32</td>
<td>3.01</td>
</tr>
<tr>
<td>DU4-35N</td>
<td>No</td>
<td>35</td>
<td>2.72</td>
<td>2.66</td>
<td>4.25</td>
<td>3.49</td>
<td>0.24</td>
</tr>
<tr>
<td>DU4-35Y</td>
<td>Yes</td>
<td>35</td>
<td>3.19</td>
<td>3.11</td>
<td>4.75</td>
<td>3.65</td>
<td>1.67</td>
</tr>
</tbody>
</table>

When hydrogen was released from an in-cabin point, the hydrogen concentrations inside the cabin increased in the presence of winds unlike the release of hydrogen from an underfloor point which caused the hydrogen concentrations to decrease in the presence of winds. This was accounted that the winds blowing toward the opened window made it difficult for accumulating hydrogen in the cabin to escape from the window.

4. CONCLUSIONS
In this hydrogen leakage test with a window of the test vehicle kept open to simulate a post-side-crash condition, hydrogen concentrations in the cabin were measured and the following results were obtained:

1) When 118NL/min of hydrogen was released from an underfloor point (positions A–C) with a nozzle diameter of 4 mm for a duration of 30 sec or longer, the maximum hydrogen concentrations at various positions in the cabin exceeded 2%.
2) When 69NL/min or more hydrogen was released from rear underfloor position C continuously, the maximum hydrogen concentrations in the cabin exceeded 4%.
3) When the nozzle diameter was 2 mm or less, the hydrogen concentrations in the cabin did not exceed 2%.
4) The in-cabin hydrogen concentrations declined with the decrease of nozzle diameter.
5) The in-cabin hydrogen concentrations rose with the increase of hydrogen leakage flow rate.
6) The presence of winds significantly affected the hydrogen concentrations in the cabin.

The above findings indicated that hydrogen concentrations inside the cabin can rise above 4% even if the hydrogen leakage flow rate is within the allowable limit of 118 NL/min. In addition, since the leakage flow rate affects hydrogen concentrations in the cabin, it is not appropriate to use helium in hydrogen leak tests. Also, because wind conditions influence in-cabin hydrogen concentrations, it is necessary to introduce common wind-related specifications in hydrogen leak tests.

ACKNOWLEDGEMENTS
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REFERENCES
Comparison of the U.S. and European Approaches to Passenger Train Fire Safety

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ABSTRACT

The Federal Railroad Administration (FRA) approach to passenger rail equipment fire safety requires the use of primarily small-scale flammability and smoke emission tests and performance criteria for interior materials, such as seats and wall and ceiling panels; and fire endurance tests for structural components, such as floors. The individual test methods measure one or more different fire performance characteristics: ignition resistance, flame spread, and smoke emission. In addition, FRA regulations include requirements for conducting fire safety analyses for new and existing equipment; and requirements for the inspection, testing, and maintenance of fire safety related equipment.

The European Committee for Standardization (CEN) has developed a Technical Specification, CEN TS 45545, based primarily on existing fire safety requirements for passenger railway rolling stock from the International Union of Railways (UIC) and individual European countries, as well as additional research sponsored by CEN.

This paper describes the results of a preliminary comparison of fire safety and related emergency systems requirements of CEN TS 45545 with current FRA regulations.

KEYWORDS: passenger train fire safety; Federal Railroad Administration; 49 CFR, Part 238; CEN, CEN TS 45545

INTRODUCTION

Although the number of fires occurring on passenger rail vehicles has been historically low, the consequences, when a fire does occur, can be catastrophic, depending on the location of the train and the operating environment, particularly if the fire occurs at night or in a tunnel. Examples include fires that occurred: on Amtrak intercity trains in Gibson, CA (1983), Bourbonnais, IL (1999), and Miriam, NV (2011); on Euroshuttle trains in the Channel Tunnel (1996 and 2008); and on the Kaprun, Austria “ski-train” (2000).

Accordingly, fire safety is an area of particular importance for inter-city passenger and commuter railroad operations. A “systems” approach to fire safety addresses passenger rail equipment design and materials for fire prevention, fire detection and suppression, passenger evacuation, and the interrelationship between these elements. The Federal Railroad Administration (FRA) and other U.S. agencies and organizations, individual European countries, the International Union of Railways UIC,
and most recently, CEN, have all developed performance requirements for passenger rail vehicles, intended to provide such a “systems” approach for passenger safety that includes but extends beyond fire behavior test methods and related performance criteria.

For convenience, the term “requirements,” as used in this paper, generically includes: regulations, standards, rules, specifications, guidelines, recommendations, and recommended practices. It should be noted that regulations and rules are the only requirements that can be and usually are legally enforceable unless other requirements are included in contracts or jurisdictional codes.

The various required fire test methods and criteria and other requirements described in this paper are presented only in summary form. Accordingly, the actual complete documents must be reviewed by the reader for complete understanding and to ensure compliance with all specific requirements.


The European Committee for Standardization (CEN) has developed a technical specification (TS) for the fire safety of rolling stock, CEN TS 45545 Railway Applications - Fire Protection on Railway Vehicles [3].

This paper describes the results of a preliminary study conducted by the John A. Volpe National Transportation Systems Center (Volpe Center) that compares the fire safety requirements of the new CEN TS 45545 with current FRA regulations and other U.S. requirements.

**FRA REQUIREMENTS**

FRA’s mission is to promulgate and enforce railroad safety regulations; administer railroad assistance programs; conduct research and development in support of improved railroad safety and assist in guiding national railroad transportation policy.

FRA has long recognized the importance of maintaining and improving the level of passenger train fire safety. In 1999, as part of the passenger rail equipment safety standards rulemaking process required by the U.S. Congress, FRA issued regulations in 49, CFR, Part 238 [4] that include fire safety requirements for new and existing passenger cars and locomotives [5].

Section 238.103 and Appendix B of Part 238 require that railroads comply with specific fire behavior tests and performance criteria for interior materials used in new passenger cars and locomotives. Based primarily on small-scale test methods that demonstrate fire characteristics of individual materials, the FRA flammability, smoke emission, fire endurance, and other requirements for passenger rail equipment comprise a prescriptive set of design specifications that historically have been used to evaluate material fire performance. This approach provides a screening device to allow interested parties to identify particularly hazardous materials and to select preferred combinations of individual components that comply with the tests and performance criteria. Material suppliers can thus independently evaluate the fire safety performance of their own materials. (It is noted that the 1999 rule is based on recommended fire safety guidelines for passenger rail car material selection that FRA first published in 1984 [6] and updated in 1989 [7]; which, in turn, were adapted from recommended fire safety practices for rail transit vehicle materials selection published in 1984 by the Federal Transit Administration (FTA) (formerly Urban Mass Transportation Administration (UMTA)) [8].

In addition to the individual material tests, a floor assembly fire endurance test is required. A seat assembly test with heat release rate (HRR) criteria is permitted as an alternative to the small-scale testing and performance criteria for individual seat component materials; a fire hazard analysis is also
required to account for the railroad operating environment, including acts of vandalism (such as arson).

Part 238 also requires that railroads complete written fire safety analyses for new and existing passenger rail cars and locomotives. The FRA objective is to ensure that fire safety considerations and features in the design of the equipment reduce the risk of personal injury and equipment damage caused by fire to an acceptable level. The railroads must conduct written analyses for new equipment using a formal safety methodology, such as MIL-STD 882 [9] for categorizing the risk of safety mishaps and hazards by their severity and probability. The following items must be included in those analyses:

- Identification, analysis, and prioritization of fire hazards inherent in equipment design.
- Equipment design and material selection for fire resistance for time to detect fire and safely evacuate the passengers and crewmembers, if a fire cannot be prevented or extinguished. Factors to consider include:
  - Potential ignition sources,
  - Type, quantity, and location of materials, and
  - Availability of rapid and safe egress to the exterior of the equipment under conditions secure from fire, smoke, and other hazards.
- Ventilation system in the equipment does not contribute to the lethality of a fire.
- Train component overheat protection if necessary.
- Fire or smoke detection system in each normally unoccupied compartment that contains a fire hazard during operation of train, as necessary to ensure time for safe evacuation of passengers and crewmembers from that compartment (i.e., closet, baggage compartment, food pantry, etc.).
- Proper type and size of portable fire extinguisher, if necessary for occupied or unoccupied compartments; each passenger car must have at least one portable fire extinguisher (per Part 239 [11]).
- Proper size and type of fixed, automatic fire-suppression system in any unoccupied train compartment that contains a fire hazard, where practical and necessary to ensure sufficient time for safe evacuation of passengers and crewmembers from the train.
- Explanation of how safety issues are resolved in equipment design and selection of materials to reduce the risk of each fire hazard.
- Description of analysis and testing necessary to demonstrate that fire protection approach taken in the equipment design and material selection complies with Part 238.

Analysis for materials used in existing passenger equipment materials must include both consideration of different categories of rail service, and factors, such as potential ignition sources; type, quantity, and location of materials used in the equipment; and the availability of safe egress to the exterior of the equipment under conditions secure from fire, smoke and other hazards.

Part 238 also requires that railroads develop and follow an inspection, testing, and maintenance plan for fire safety-related equipment.

An update to the FRA fire safety requirements was issued in 2002, which included clarification of certain fire performance requirements, as well as responses to comments to the 1999 final rule [10].

As noted above, in addition to the Part 238 fire safety requirements, Part 239 requires that each passenger car and locomotive be equipped with a fire extinguisher [11].

To ensure passenger safety, Part 239 also requires that railroads consider, in developing their emergency preparedness plan(s), the special circumstances of evacuating passengers in tunnels more than 308 m (1,000 ft) long, by providing emergency lighting, access to emergency exits, effective emergency communications, and other options for assistance from other trains [12].

In addition, Part 238 and Part 239 contain extensive requirements relating to emergency egress, including: the type, location, and size of emergency exits and the marking of such door and
emergency window exits, as well as emergency lighting, and emergency communication systems [13][14].

In 2008, FRA issued enhancements to the emergency system requirements in Part 238 [15] and in 2012, issued a new notice of proposed rulemaking to further enhance those requirements [16].

**APTA RECOMMENDED PRACTICE FOR FIRE SAFETY ANALYSIS FOR EXISTING RAIL PASSENGER VEHICLES**

Following FRA issuance of the 1999 final rule, an industry group, the American Public Transportation Association (APTA) developed a manual of standards and recommended practices for passenger rail equipment to supplement and provide guidance for complying with the FRA regulations. A task force representing system operators, the FRA, technical experts, and other interested parties developed a recommended practice to provide more specific guidance to railroads to identify, analyze, and resolve the risk of fire events for existing passenger equipment [17].

The APTA fire safety recommended practice also refers to APTA standards for passenger equipment emergency lighting systems, emergency egress and access signage, and low-location exit path marking systems developed during the same process described above, and which were updated in 2007.

**NFPA 130 STANDARD FOR FIXED GUIDEWAY TRANSIT AND PASSENGER RAIL SYSTEMS**

The National Fire Protection Association (NFPA) is an organization that develops and publishes life safety and fire protection codes and standards for a variety of U.S. buildings and other facilities. The NFPA codes and standards are developed by consensus and are revised periodically by committees that include system operators, regulators, fire departments, fire protection engineers, technical experts, and other interested parties. The NFPA standard (NFPA 130) for fixed guideway (e.g., rail) transit systems was first adopted in 1983 [18]. NFPA 130 is a comprehensive approach because it includes fire safety and emergency evacuation-related requirements for vehicles, stations, and trainways. However, NFPA 130 requirements are not enforceable unless adopted by the local authority having jurisdiction (e.g., State or city, or local fire department). In 1990, NFPA 130 adopted the 1984 FTA table of recommended fire tests and performance criteria in its entirety [19]. The scope was expanded to include passenger rail vehicles in 2000 [20], while passenger rail stations and trainways were added in 2007 [21]. In 2007, the vehicle chapter was revised to update the table of tests and performance criteria to reflect, with few exceptions, the FRA requirements contained in the table in Appendix B of Part 238. The latest edition was published in 2010 and included a reorganization of the vehicle structural fire testing requirements [22].

**FRA AND NFPA 130 FIRE PERFORMANCE TEST REQUIREMENTS**

The individual fire behavior test methods cited by FRA and the Vehicle chapter of NFPA 130 measure one or more of four different fire performance characteristics including the following:

- Ignition resistance,
- Flame spread,
- Smoke emission, and
- Fire endurance.

Table 1 shows the passenger rail vehicle tests and performance criteria common to both FRA Part 238, Appendix B and NFPA 130 requirements.

The requirements are based primarily on two small-scale (ASTM International, formerly American Society for Testing and Materials) individual material test methods:
Table 1. U.S. passenger rail equipment fire behavior tests and performance criteria.

<table>
<thead>
<tr>
<th>COMPONENT/FUNCTION</th>
<th>FIRE BEHAVIOR</th>
<th>TEST METHOD</th>
<th>PERFORMANCE CRITERIA a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat cushions &amp; mattresses, armrests, seat pads</td>
<td>Flame Spread</td>
<td>ASTM E 162</td>
<td>I ≤ 25</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td>ASTM E 662</td>
<td>D_s (1.5): 100 D_s (4.0): 175</td>
</tr>
<tr>
<td>Fabrics (upholstery, curtains, etc.)</td>
<td>Flame Spread</td>
<td>14 CFR 25.853 (a)</td>
<td>Flame Time ≤ 10 s Burn length ≤ 15.2 cm (6 in)</td>
</tr>
<tr>
<td></td>
<td>Resistance</td>
<td>ASTM E 662</td>
<td>D_s (4.0): ≤ 200 (for both coated and uncoated)</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite seat / mattress assembly</td>
<td>Heat Release Rate</td>
<td>ASTM E 1537</td>
<td>Max HRR &lt; 80 kW/m² THR &lt; 25 MJ (10 min)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASTM E 1590</td>
<td>ML &lt; 3 lb (10 min) Max HRR &lt; 100 kW/m² THR &lt; 25 MJ</td>
</tr>
<tr>
<td>Panel, partition, wall, ceiling</td>
<td>Flame Spread</td>
<td>ASTM E 162</td>
<td>I ≤ 35</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td>ASTM E 662</td>
<td>D_s (1.5.0): 100 D_s (4.0): 200</td>
</tr>
<tr>
<td>Other seat materials, thermal and acoustical insulation, HVAC ducting, etc.</td>
<td>Flame Spread</td>
<td>ASTM E 162</td>
<td>I ≤ 35</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td>ASTM E 662</td>
<td>D_s (1.5): 100 D_s (4.0): 200</td>
</tr>
<tr>
<td>Light diffusers, windows, etc.</td>
<td>Flame Spread</td>
<td>ASTM E 162</td>
<td>I ≤ 100</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td>ASTM E 662</td>
<td>D_s (1.5.0): 100 D_s (4.0): 200</td>
</tr>
<tr>
<td>Elastomers</td>
<td>Flame Spread</td>
<td>ASTM C 1166</td>
<td>Pass (burn length ≤ than 10.2 cm (4 in)</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td>ASTM E 662</td>
<td>D_s (4.0): 200</td>
</tr>
<tr>
<td>Floor covering</td>
<td>Flame Spread</td>
<td>ASTM E 648</td>
<td>CFR &gt; 0.5 watts/cm² (5 kW/m²)</td>
</tr>
<tr>
<td></td>
<td>Smoke Emission</td>
<td>ASTM E 662</td>
<td>D_s (1.5): 100 D_s (4.0): 400</td>
</tr>
<tr>
<td>Small parts with surface area &lt; 100 sq cm (16 sq in)</td>
<td>Heat Release Rate</td>
<td>ASTM E 1354</td>
<td>Avg HRR (q_{avg}) ≤ 100 kW/m²</td>
</tr>
<tr>
<td>Floor structure</td>
<td>Fire Endurance</td>
<td>ASTM E 119</td>
<td>Avg specific extinction area (σ f) ≤ 500 m²/kg over same 180-second period</td>
</tr>
</tbody>
</table>

a The actual test requirements and performance criteria include several compliance notes.

- ASTM E 162, Standard Test Method for Surface Flammability of Materials Using a Radiant Energy Source [23], (with a variant for cellular foams, ASTM D-3675 [24]), and

Several other test requirements are specified for certain other individual material categories and functions, including:

- ASTM C 1166, Standard Test Method for Flame Propagation for Dense and Cellular Elastomeric Gaskets and Accessories [27], and
- 14 CFR, Part 25, Subsection 25.853 (a) Compartment Interiors for fabrics [28].

All of the test methods are designed to study aspects of a material's fire behavior in a fixed configuration and exposure, with the exception of ASTM E 119, Standard Test Methods for Fire Tests of Building Construction and Materials, which is a real-scale fire endurance test [29].

(ASTM E 1354, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter) [34] is permitted for certain small parts. NFPA 130 also includes an extensive section of vehicle electrical wire and cable flammability and smoke requirements. Although FRA does include electrical system requirements in Part 238 [35], no specific fire safety test requirements for electrical wire and cable installed in passenger cars are included in Appendix B of Part 238.

HISTORICAL EUROPEAN PASSENGER ROLLING STOCK REQUIREMENTS

UIC 564-2 covers passenger rolling stock design for international service (including Europe) [35]. As a general guideline for vehicle design, UIC Code 564-2 states that: “the coach design and interior fittings must above all prevent the spread of fire” and accordingly includes requirements for:

- Vehicle material flammability to reduce potential ignition and flame spread, and smoke emission,
- Compartmentation (to prevent spread of fire from one vehicle to another),
- Electrical systems, fire detection in engine compartments,
- Fire extinguishers, and
- Fire alarms.

The German DIN 5510 [36], French NF 101 and 102 [37][38], and British BS 6853 [39] fire safety requirements for railway vehicles, all issued in the late 1980 and 1990s, contain similar provisions for small-scale flammability and smoke emission tests to evaluate individual component materials. A major commonality is the inclusion of more stringent fire performance requirements for interior materials installed in rolling stock operating in certain environments, such as in tunnels or in overnight service with sleeping cars; and less stringent requirements for exterior materials. The German DIN and French NF standards also reference the UIC 564-2 newspaper “pillow” ignition source for the seat assembly test. Although the British BS 6853 standard also includes a seat assembly test requirement, that test is considered to be more stringent because it uses a wooden “crib” as an ignition source. In addition, the German DIN 5510, French NF 103 [40], and British BS 6853 standards all include emergency evacuation-related requirements for railway rolling stock, including exit doors and/or emergency lighting.

CEN TS 45545

CEN TS 45545 [3] is based primarily on previously existing fire safety requirements for railway vehicles developed by UIC and by several European countries, including Germany, France, and the United Kingdom; as well as an earlier extensive research program sponsored by the European Railway Research Institute (ERRI). That research program was initiated following the issuance of the 1991 UIC 564-2 standard, and included a series of tasks and reports describing results for the analysis of small-, real-, and full-scale HRR fire performance tests. The final ERRI report [41] also referenced the activities of the CEN Technical Committee (TC) 256, responsible for developing a common European Union standard for passenger railway rolling stock.

CEN issued technical directives in 1996 and 2001 for the inter-operability of the Trans-European high-speed and conventional rail systems in terms of safety, reliability, etc. European standards (EN) must be translated into a national standard in all 30 member countries, which guarantees that a manufacturer has easier access to the markets of all these European countries. Member countries must also withdraw any conflicting national standard, because the EN prevails over any national standard. The CEN 45545 Joint Working Group, composed of the CEN TC 256 Working Group 1 and the CENELEC TC 9X Working Group 3 (relating to electro-technical standardization), developed a basic framework for the contents of the proposed EN 45545 standard, based primarily on hazards in the different passenger railway rolling stock operating environments.
The *FireStarr* research program was initiated in 1997 with funding from CEN and industry partners. A 2001 report [42] described the results of nine extensive fire research work areas, including risk and scenario selection; selection of 31 materials to be tested; selection of small- and large-scale ignitability; flame spread, heat release rate, and smoke and toxic gas tests; conduct of tests of representative railway vehicle structural, furniture, and electro-technical materials (excluding cable); and selection of performance criteria. A set of principles was developed for a reaction-to-fire-material test classification system related to the four selected operating categories that are described in the next section. The stated intent of the *FireStarr* research was to include proposals to be further developed by the CEN and CENELEC committees. Accordingly, the CEN/CENELEC Joint Working Group sponsored additional research and discussion activities over the following years for the proposed *EN 45545* standard.

In 2009, CEN approved the contents of the proposed *EN 45545* as a TS which is now available for provisional application at the national level. Although it is possible to keep a national standard in force in parallel to the TS, the *EN* designation will require implementation by each member country at the national level and withdrawal of any conflicting national standard. Accordingly, a special working group was formed to complete additional revisions to clarify certain proposals and to come to common agreement, particularly for some requirements in certain sections and parts, to enable *TS 45545* to become an *EN 45455* standard.

*CEN TS 45545* for rolling stock fire safety is comprised of seven parts that are summarized below.

**Part 1, General** includes definitions, operation and vehicle design categories, fire safety objectives and general requirements. The objectives are to: minimize the probability of a fire starting, to control the rate and extent of fire development, and to minimize impact on passengers and train staff. The scope includes different ignition models involving a variety of ignition sources, in order to reduce the risk of a fire spread resulting from accidental ignition by arson or a technical defect, through occupied areas; and endangering passengers and crew by obscuration of escape routes and presence of toxic fumes. The cited test methods are based on *FIRST* (flammability, ignition, Rate of Heat Release, smoke, and toxicity).

The four categories of passenger railway rolling stock operation are summarized as follows:

1: Not designed to operate in or on underground sections, in tunnels, and/or on elevated sections, which can be stopped with minimum delay, after which immediate side evacuation to place of ultimate safety is possible.
2: Designed to operate in or on underground sections, tunnels and/or on elevated sections, where side evacuation to stations or emergency station ultimate safety is reachable within a short running time.
3: Designed to operate in or on underground sections, tunnels and/or on elevated sections, where side evacuation to stations or emergency stations (place of ultimate safety) is reachable within a long running time.
4: Designed to operate in or on underground sections, tunnels and/or on elevated sections, without side evacuation available to stations or emergency stations (place of ultimate safety) is reachable within a short running time.

Rolling stock vehicles are classified according to their design:

- A: Part of automatic train having no emergency-trained staff onboard,
- D: Double deck vehicles,
- S: Sleeping and couchette vehicles, or
- N: All other standard vehicles.

**Part 2, Requirements for Fire Behavior of Materials and Components** includes a classification system for different hazards, based on the operation category and the vehicle design category (see Table 2).
Table 2. Hazard Classification Levels (HL) (condensed and adapted from Table 3 in Part 2).

<table>
<thead>
<tr>
<th>Operation Category</th>
<th>(Vehicle) Design Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>1</td>
<td>HL 1</td>
</tr>
<tr>
<td>2</td>
<td>HL 2</td>
</tr>
<tr>
<td>3</td>
<td>HL 2</td>
</tr>
<tr>
<td>4</td>
<td>HL 3</td>
</tr>
</tbody>
</table>

Depending on the hazard level, the interior materials (and to a lesser extent, the exterior structural materials), are required to comply with stringent test requirements, with the highest hazard level designated as HL3. However, as Table 2 shows, the hazard levels for N, A, and D vehicle categories, based on the four operation categories, are all identical. Although all vehicle design categories under Operation Category 4 are at the highest hazard level, only sleeping and couchette cars (S) have higher hazard levels for Operation Categories 1-3.

The remainder of Part 2 includes general principles for testing requirements; including recognition that material reaction to fire depends on the location of the material or components, the shape and layout of materials, the direct surface exposed, and the relative mass and thickness of the materials. The materials are further classified according to their interior or exterior location, and their specific use: structural, furniture, electromechanical, or mechanical.

Part 2 contains an extensive comprehensive set of tables listing the required tests and performance criteria for the various categories of materials, based on the hazard level.

It is beyond the scope of this paper to provide a detailed description and comparison of all the extensive fire test requirements and performance criteria contained in Part 2 (and other parts) of CEN TS 45545, with FRA Part 238, Appendix B, and NFPA 130. However, it is noted that flammability and smoke emission requirements for interior materials primarily rely on small-scale tests: For example, ISO 5658-2 [43] (similar to ASTM E 162, except with different type of criteria); ISO 5659-2 [44] (similar to ASTM E 662, except with different radiant heater used to heat sample and sample orientation, higher heat flux, as well as additional criteria; ISO 5660-1 [45] (equivalent to ASTM E 1354, with a higher heat flux and different criteria); and ISO 9239-1 [46] (similar to ASTM E 648) for floor covering (but with different criteria, depending on the hazard level).

In addition, a complete passenger seat assembly is required to be tested using a furniture calorimeter (similar to ASTM E 1537) according to ISO/TR9705-2 [47]. However, the specified gas burner ignition source in one of the annexes to Part 2 requires fewer tubing holes (27 versus 42) than ASTM E 1357, so the effect on the gas flow ignition source is unclear. In addition, another annex contains a detailed description of the required vandalism test for the seat assembly cushion that must be conducted prior to performing the fire test. The maximum average HRR permitted for the highest hazard level (HL3) for sleeping cars is much lower than the FRA/NFPA 130 criteria applicable for all passenger cars (20 versus 80 kw/m²).

Lastly, Part 2 requires that materials be tested according to a French NS toxicity test [48] with maximum limits for eight gases, including carbon monoxide (CO), hydrogen cyanide (HCN), and hydrogen fluoride (HFL). The limits are based on reference values for personal exposure to Immediately Dangerous to Life and Health (IDLH) limits developed by the U.S. National Institute for Occupational Safety and Health.

A summary of the other five parts includes:

- **Part 3, Fire Resistance Requirements for Fire Barriers:** to maintain fire and heat separation between two adjacent areas of the vehicle for minimum 15- or 30-minute time periods under specified conditions.
• **Part 4. Fire Safety Requirements for Rolling Stock Design**: to minimize the start of a fire, delay fire development, and aid evacuation.

• **Part 5. Fire Safety Requirements for Electrical Equipment**: to minimize a fire during operation as a result of technical defects of the electrical equipment and wiring.

• **Part 6. Fire Safety Requirements for Fire Control and Management System**: for fire detection, alarms, equipment shutdown, and fire extinguishers, emergency signs, and emergency lighting.

• **Part 7. Fire Safety Requirements for Flammable Liquid and Flammable Gas Installations**: to prevent a fire from occurring and spreading by leakage of flammable liquids or LPG used in traction or auxiliary power units, or heating or cooking gases.

The TRANSFEU (Transport Fire Safety Engineering in the European Union) project continues to further investigate toxicity for public transport guided systems including passenger railway rolling stock. A periodic newsletter describing the progress of the TRANSFEU work is available at www.transfeu.eu.

**SUMMARY**

The CEN TS 45545 fire safety approach is similar to that of the FRA Part 238 approach, in that only requirements for rolling stock (e.g., passenger equipment) are specified, although the objectives of both sets of requirements are to minimize the occurrence and impact of a fire and provide adequate time for evacuation. Although several of the fire safety test methods and performance criteria requirements cited in FRA Part 238, Appendix B and the vehicle chapter of NFPA 130 are somewhat similar to TS 45545, clear differences exist, including the TS 45545-specified hazard levels for vehicles, based on operation environments, and rolling stock design. In addition, TS 45545 requires HRR tests with performance criteria that apply to more vehicle components than the FRA/NFPA 130-required seat and mattress assemblies (and small parts); and also includes wire and cable fire performance tests and criteria. Finally, TS 45545 includes toxicity requirements which FRA does not.

Part 238 and Part 239 also contain requirements for equipment, such as fire extinguishers, and other fire safety related equipment and systems, based on the results of risk analysis. In addition, FRA has extensive emergency preparedness-related requirements, including emergency plans, as well as emergency evacuation-related equipment, such as emergency exits and emergency lighting. The NFPA 130 approach considers the environment of the entire rail operating system because it includes requirements for stations and trainways, as well as vehicles; and also includes requirements for emergency preparedness plans. TS 45545 also contains specific requirements for fire extinguishers, ventilation systems, fire detection and suppression systems; and emergency evacuation systems, including emergency exits and emergency lighting.

Further review and more extensive analysis are necessary to fully understand the similarities and differences in the respective U.S. and TS 45545 approaches to ensure passenger rail equipment safety.

**REFERENCES**


4. FRA. 49 CFR. Part 238, Subpart B, General Requirements; Subsection 238.103, Fire Safety and Appendix B. USDOT. Office of the Federal Register, National Archives and Records Administration, Washington, DC. As of October 1, 2011.


233


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ABSTRACT
Bus engine compartments may be designed in many different ways, but they have enough commonality to make a general test method useful. A test apparatus was developed to test and compare different fire suppression systems. Various fire sources are placed at pre-determined positions in order to test different fire scenarios such as large fires, small fires, spray fires, hidden fires, and glowing fires. The test method comprises a 4 m³ enclosure with fan, apertures, engine mockup components with hot surfaces and obstructions. This creates a generic cluttered space which reflects the environment found in real bus and coach engine compartments. In order to fully characterise a suppression system it is tested against several different fire scenarios. The results are used to give an overall indication if the system has an acceptable performance level, as well as to point out strengths and weaknesses of the system for different fire scenarios, driving conditions, and hazard levels.

KEYWORDS: bus fires, coach fires, fire suppression, engine compartment, performance evaluation, test method, standard

INTRODUCTION
Bus and coach fires are a big problem in society. Statistics from Sweden show that approximately 1% of all buses catch fire each year [1]. This incurs large losses to carrier and insurance companies. Though losses of lives caused by bus fires are relatively uncommon there are examples of disastrous bus fires in recent years such as Wuxi, China, 2010 (24 fatalities) [2], Uttar Pradesh, India, 2008 (63 fatalities) [3], Hannover, Germany, 2008 (20 fatalities) [4] and Wilmer, USA, 2005 (23 fatalities) [5].

A majority of the fires start in the vehicle’s engine compartment [1, 6]. This is explained by the high working temperatures that result from strict regulations on noise and emission levels. Heavily used vehicles and poor maintenance may also contribute to the fires. Full scale experiments [6] have shown that if a large fire breaks out in the engine compartment there might be only ~5 minutes available for evacuation before the passenger compartment is filled with toxic gases at lethal levels.

Given the fact that most fires start in the engine compartment, adequate active fire protection systems for engine compartments are advantageous both in terms of passenger safety, carrier and insurance company economy, and general public resource management. Thus, various organisations have identified the installation of automated fire suppression systems in the engine compartments as an important fire safety measure [7-10]. Furthermore, some insurance companies and individual carriers already require fire suppression systems in buses. However, there is still no legislative demand for this course of action, nor an international standard for testing bus engine compartment fire suppression systems.

SP has been working on improving fire safety on buses since 2005 using a holistic approach addressing various tools and issues such as statistics, risk analysis, material properties, as well as test methods for interior materials, fire partitions and suppression systems [6, 11-13]. An example of the

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1 Buses and coaches are referred to as “buses” in the following text.
results from this work is part of the amendment of Reg No 118 [14, 15] which was decided by the United Nations Economic Commission for Europe (UNECE) in 2011. In a joint document by France, Germany, Norway, and Sweden, presented at UNECE in 2010, automatic fire suppression systems in the engine compartments in buses was pointed out as a prioritized issue [16].

Standardized performance testing and validation of detection and suppression systems used in automatic fire suppression systems is needed. Due to the complexity of the issue, SP has divided the project into two parts. Developing a test methodology for fire suppression performance is the first step and is now being finalized; the next step will be to develop a method to test the performance of fire detection systems.

INTRODUCTION TO SP METHOD 4912
Bus engine compartments may be designed in many different ways, but they have enough commonality to make a general test method useful [1]. SP Method 4912 describes a new concept to test and validate the fire suppression performance of different suppression systems in a repeatable and reproducible way. A broad reference group including more than 80 companies such as bus manufacturers and operators, transport authorities, insurance companies, fire investigators and suppression system manufacturers have given valuable feedback to the project. There have been more than 450 pretests involving 10 fire suppression system manufacturers and with several different types of suppression agents, such as ABC- and BC-dry chemical, water mist with or without foam and additives, water spray and foam systems, aerosol and clean agent. This paper briefly describes the test methodology and the process with which it was developed. More information about the test method can be found in the SP Method 4912 [17].

The results from the test methodology are used to give an overall indication if the system has an acceptable performance level, as well as to point out strengths and weaknesses of the system based on different fire scenarios and driving conditions.

NEED FOR A NEW STANDARD
Fire suppression system manufacturers produce systems with different suppression agents and different agent distribution technologies. Currently there are no international standards to evaluate and compare those different suppression systems in a repeatable and reproducible way. However, a few related standards exists which have provided guidance to the development of a new test methodology. Especially the following test methods have been reviewed and used as a source of input: Swedish Fire Protection Association Guideline SBF 128 [18], Australian Standard 5062 [19], European Standard EN-3 [20], Underwriters Laboratories Standard UL 1254 [21], International Maritime Organization Standard IMO 1165 [22] and SP Technical Research Institute Method 2377 [23].

REQUIREMENTS ON A TEST METHODOLOGY
In order for the new test methodology to be valuable the test methods must be repeatable, which means that the test method must be able to produce the same result at another time. In practice this means that the fire scenarios must be predetermined and the fire sources cannot be randomly spread in the test fixture or chosen by the test operators. The test also needs to be reproducible, meaning that it must be possible to reproduce the test setup at another location and get the same test results. This requires a test apparatus that is not too complicated to reproduce. It should not involve, for example, a specific engine type as this engine type might go out of production and be difficult to obtain. Furthermore it must be possible to obtain the same pretest condition before every new test. The test apparatus should not be damaged after a series of testing making the 20th test different from the first. Additionally, the test should have a realistic fire challenge, which means that the test must re-create potential fire scenarios from the real world that the fire suppression systems should be able to handle. Moreover, it is important that the test not wrongly favor or disqualify a certain agent or suppression technology. The test should also be designed in a way that a modification made on the suppression system in order to receive a better test result also provides a better suppression performance in a real fire event. Furthermore, it is preferable if the test method not only gives the information: pass or fail, but can rate systems in a manner that makes it possible to compare different systems with the
possibility to choose a better system if a higher safety level is desired. This also motivates manufacturers to improve systems and get a higher rating. In this case, the rating system of hand extinguishers is a model. Finally, the tests should not be too expensive to perform.

INVESTIGATION OF ENGINE COMPARTMENT CHALLENGES

In order to develop a realistic test apparatus, several buses were examined. More about this process can be found in reference [1]. The survey was limited to heavy diesel fueled buses with rear mounted engine compartments as those represent the vast majority of buses. Engine compartments were found to have several properties challenging a fire suppression system and some observations are presented below.

Geometry of bus engine compartments

The size of bus and coach engine compartments is highly variable and the gross volume usually differs between 2 – 6 m³. Engine compartments can have different shapes, and do not need to be rectangular. In profile, the floor is often slightly inclined and the ceiling may have a stepped shape. The test apparatus (see Figures 1 and 2) have a typical engine compartment size with a gross volume of 4 m³.

![Test apparatus for SP Method 4912](image)

Ignition sources

A fire in an engine compartment can start due to several reasons. It might for example be leaking fuel or material in contact with hot surfaces as well as electrical failures or overheated components. A fire can start at many locations, in particular: at the turbo charger or exhaust system, particle filter, alternators, starter motor, electrical cables and boxes, ping tank etc. To simulate the many possible ignition sources in SP Method 4912, multiply fire sources are located in different areas of the test apparatus.
Obstructions
Engine compartments can sometimes be cluttered and potential fire sources can be hidden behind obstructing engine components, cylinders, boxes, tubes and balks. If the obstructions are hiding the fire source, it might be very difficult for the suppression agents to reach and suppress the fire. Figure 3 shows an example of an engine compartment with typical obstructions.

The SP 4912 test apparatus is equipped with a dummy engine mockup and exhaust system. Since an engine compartment fire source can be concealed to different degrees, the test apparatus are equipped with obstructions concealing the fire sources according to the following categories:
1. Non-obstructed fire
2. Semi-obstructed fire behind one row of tubes
3. Semi-obstructed fire behind two rows of tubes
4. Fully obstructed fire behind a concealing plate

Figure 4 shows an example of a fire test. According to the test method, the nozzles of the suppression system are to be positioned in the ceiling or on the rear wall of the test apparatus so that the test fires are obstructed by the row of tube, and thus simulating scenarios where the system must be able to extinguish the fire even if it is located behind engine components.

Figure 4 Example of a test fire setup. The fire source is semi-obstructed below two rows of obstruction tubes

Air flow

Engine compartments are usually well ventilated by the engine fan. However, depending on the bus construction and driving conditions the ventilation rate in the engine compartment can range from very small to very high air flow. If the suppression system activates while the engine is off, the air movement will only come naturally through the apertures of the engine compartment, but if the engine is running with high rpm, the engine fan may create a very high air flow through the engine compartment. The rate of air flow will have a great impact on the suppression performance as the air flow may carry away the suppression agent and introduce more oxygen to the fire. To simulate these conditions in the test method, a fan with the same dimension and air flow as fans used in some engine compartments generates air flows according to Table 1. A picture of the fan used for the testing is shown in Figure 5.

Table 1 Air flow in SP Method 4912

<table>
<thead>
<tr>
<th>Air flow rate</th>
<th>Forced mass flow of air</th>
<th>Simulated driving conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High air flow</td>
<td>3 m³/s</td>
<td>Engine running with high speed</td>
</tr>
<tr>
<td>Medium air flow</td>
<td>1.5 m³/s</td>
<td>Engine running with low speed or on high idle</td>
</tr>
<tr>
<td>Low air flow</td>
<td>0.5 m³/s</td>
<td>Engine on low idle</td>
</tr>
<tr>
<td>No forced air flow</td>
<td>0 m³/s</td>
<td>Engine off</td>
</tr>
</tbody>
</table>
Flammable liquids and solids
Engine compartments include many flammable liquids and solids. Depending on the construction it may contain tens of liters of oil. Some of the oil is stored under pressure. A leakage of pressurized diesel or hydraulic fluid might result in a spray that wets hot engine components and, if ignition occurs, creates a quickly developing fire. Engine compartments may also include flammable solids such as plastic containers, rubber hoses and acoustic insulation made e.g. of foam or lump material.

SP Method 4912 includes diesel pool fires, diesel spray fires, fires involving oil leaks and deposition, as well as fires in solid materials (fiberboard sheets and wood crib). The fiberboard sheets are soaked in diesel oil and stand vertically in a diesel pool tray. They simulate an engine compartment fire involving both flammable liquid and solids, for example acoustic insulation absorbing fuel. Some tests have been made with plastic sheets in order to simulate a fire in plastics. The plastic sheets were not a repeatable fire source because they are melt in non-repeatable ways and do not introduce a new fire challenge compared to fiberboards. The fiberboards are soaked in diesel and thus represent a Class B-fire with the fiberboard working as a wick. Since fiberboards represent Class B fires in a more repeatable way than plastic, the plastic fuels have been replaced by fiberboard in the test methods. Figure 6 is showing a sketch of the test fire with fiberboards. The wood crib represents a glowing Class A-fire and constitutes a re-ignition threat.

Hot surfaces
The presence of hot surfaces in the engine compartment is an important fire challenge. The external surface temperature of turbo chargers and exhaust system can be in excess of 600 °C during certain conditions. This temperature is high enough to ignite the flammable liquids present in engine compartments. It also creates the risk of fuel re-ignition after extinguishment. In order to re-create the
hot surface challenge in a repeatable and reproducible way, a hollow tube with a thermal mass similar to an engine compartment turbo charger is heated from the inside with a propane burner. The tube is designed to have the same temperature profile as a turbo charger on a modern Euro 5 bus engine.

During the re-ignition fire test according to SP Method 4912, the tube is heated to 615 °C and after that the pre-heating burner is removed, simulating a hot engine which has been turned off and thus slowly starts cooling. When the tube has cooled to 600 °C a small leakage of engine oil is applied. Due to the high surface temperature of the tube, the engine oil ignites immediately and the suppression system is activated after 10 seconds. While the suppression system has a short discharge time, the oil is continuing dripping on the heated tube. The suppression system can only prevent a re-ignition if it cools and keeps the surface at a temperature roughly below 400 °C or maintains a required concentration of suppression agent for a time long enough to prevent re-ignition or coats the hot surface with a layer of suppressant. Figure 7 shows the surface temperature of the hot tube during a re-ignition test. The suppression agent is able to cool the surface, but when the stored heat in the tube is distributed back to the surface, the temperature increases again which finally might cause a re-ignition.

![Re-ignition test](image)

*Figure 7 Temperature on the hot surface during a pre-test of re-ignition protection ability*

**Fire scenarios**
As the size and character of an engine compartment fire can differ much depending on the actual circumstances, the fire scenarios in SP-method 4912 are divided into the following different categories: High fire load, low fire load, Class A-fire, hidden fire, and hot surface re-ignition, as shown in Table 2. The total heat release rate of the different fire scenarios is ranging from 5 kW to 940 kW. Figure 8 shows a fire test performed during the pre-test period.
VALIDATION OF THE TEST METHOD
When developing a laboratory test method it is very important to ensure validation from results of real-world experience and testing. Depending on the how a fire test method is developed, completely different test results and conclusions can be obtained. To validate the test method, the following steps have been essential:

1. Identifying representative test conditions and as close as possible creating realistic fire scenarios.
2. Collecting data from the users of tested suppression systems about how the suppression systems have worked in reality is a valuable source of information when trying to develop a test in accordance with reality. This information has been obtained by suppression system users such as bus operators from several different countries. Fire investigation reports where the fire source and the performance of a suppression system is also a credible source.
3. Performing full scale tests in buses with a running engine as a complement to laboratory testing. Full scale fire tests with different suppression technologies have been performed by BAM (Federal Institute for Materials Research and Testing in Germany) with SP as a partner. The suppression systems were tested with good validating results in the engine compartment of a bus with a running engine. SP has also performed full scale testing in engine compartments as commissioning testing.
SUMMARY AND CONCLUSIONS MADE FROM THE TEST RESULTS

The fire tests in the test protocol are divided into the following categories: High fire load test, low fire load test, class A-fire test, hidden fire test, re-ignition protection test and fire tests with fan ventilation. These test methods rate the suppression systems in a comparable way and provide feedback to buyers and manufacturers about the strengths and weaknesses of the systems being tested. In this way, the following information can be considered before installing the suppression system in engine compartments:

High fire load test: If the high fire load tests can be extinguished in the test setup, this indicates that the suppression system has the ability to suppress large fires. If those test fires cannot be extinguished special notice should be given to rapid fire detection in order to limit the potential for fire growth.

Low fire load test: If the low fire load tests can be extinguished in the test setup, this indicates that the suppression system has the ability to distribute the agent to several different areas in an engine compartment and that the system has the ability to suppress small fires. If those test fires cannot be extinguished special notice should be given to ensure good nozzle coverage in the engine compartment.

Class A fire test: If the Class A-fires can be extinguished in the test setup, this indicates that the suppression agent has a good ability to extinguish smaller fires in fibrous materials. If those fires cannot be extinguished this implies an increased risk of re-ignition due to smoldering material and special notice should be given to rapid fire detection and thereby reducing the risk of fire spread to insulation material and other fibrous Class A-materials.

Hidden fire test: If the hidden fires can be extinguished, this indicates that the suppression system has certain total flooding properties, i.e. the ability to suppress fires without direct application to the fire source. If those fires cannot be extinguished particular notice should be given to cover all hidden hazard areas. Suppression agent should be applied directly to those risk areas and thereby minimizing concealed and unprotected areas in the engine compartment.

Re-ignition protection testing: If re-ignition can be prevented, this indicates that the suppression system has an ability to prevent re-ignition of flammable liquid on hot surfaces in the engine compartment if the engine is shut down upon activation of the suppression system. If re-ignition cannot be prevented, special notice should be given to decreasing the risk of flammable liquid coming into contact with hot surfaces after activation of the suppression system. As an extra safety measure a second suppression agent discharge should be considered.

Fire tests with fan ventilation: If the fire tests with fan ventilation can be extinguished, this indicates that the suppression system has an ability to extinguish fires at high ventilation. If those fires cannot be extinguished particular notice should be given to turning off the fan when the suppression system is activated.

On the basis of the test result different safety levels might be chosen for different buses. An extra high safety level could for example be required for buses with elderly and disabled people.

REFERENCES

The Cost Effectiveness of On-Board Train Fire Suppression Systems in Underground Rail Transit Systems

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ABSTRACT

This technical paper evaluates the practicality, safety and economic return on the installation of on-board train fire suppression systems in underground rail transit systems where significant lengths of tunnel are involved. It presents: 1) a design for an on-board train fire detection and suppression system; 2) the capital, operating and maintenance costs for such a system; 3) typical emergency tunnel ventilation system capacities with and without on-board systems; and 4) the decrease in facility capital, operating and maintenance costs possible by the implementation of on-board systems in lieu of a more traditional tunnel ventilation system. It is concluded that the on-board train fire suppression systems are extremely cost effective.

TUNNEL AND UNDERGROUND STATION FIRE SAFETY REQUIREMENTS

NFPA 130 [1] and most tunnel ventilation design criteria recognize two types of fires – a fire on a train caused by arson (or electrical equipment failure) and a trash or luggage fire occurring on a platform or concourse. The principle characterization of a fire is its fire heat release rate (FHRR) expressed in Megawatts (MW). Other characteristics that must also be considered are the fire growth rate (usually stated in W/s²) and fire soot and carbon monoxide release rates (usually stated in grams per second (g/s)).

Trash or Luggage Fire

It is industry practice to use 1 MW as the FHRR of fires such as baggage or trash fires. Tests show this value to be quite conservative. The fully developed non-train FHRR is 1.055 MW. The fire growth rate is 46.892 W/s² and the fire growth time is 150 seconds.

Arson Fire

Although the interiors of modern rail vehicles utilize fire-retardant materials to meet the requirements of NFPA 130, it is still possible, albeit improbable, for a life threatening fire to become established on board such a vehicle. Passenger clothing, luggage, computer bags, shopping bags, backpacks, etc. carried on board by passengers can become a fuel source to raise combustion temperatures in a localized area sufficiently to overcome the fire–retardant capabilities of the adjacent vehicle’s interior components (i.e., flash-over occurs). The open, non-compartmentalized nature of the passenger area can allow a serious fire to spread through an entire car, or in the case of married cars, the entire trainset. Such fuel sources are of variable flammability, unpredictable in quantity, and may be ignited by a variety of means ranging from accidental to deliberate (i.e., arson attack using a flammable liquid as an accelerant). An arson attack is, of course, one of the worst case fire scenarios. A large but relatively short-lived initial fire starts in the interior of the vehicle as the accelerant is quickly consumed by the fire. However, other combustible fuel sources as identified above can subsequently be ignited by this fire, becoming the actual hazard with respect to fire spread and duration. The tunnel and station fire scenario on which tunnel ventilation fan capacities are based is a train interior fire caused by arson. The fully developed FHRR for an arson fire is 25.36 MW and is based on a two-car trainset fire scenario. The fire growth rate is 750.272 W/s² and corresponds to an arson incident
initiated with sufficient gasoline to cause flashover (around one-half gallon). The fire is assumed to start in the first car and then spread to the second car after 1,030 seconds.

**Undercar Fire**

The primary cause of an undercar fire is an electrical failure. The estimated FHRR is 1 MW. An undercar fire could stop a train in a tunnel and be hard to access. NFPA 130 mandated 30 minute fire rated floors to allow adequate time for the train to reach the next station or be evacuated. Underground stations typically also have manually-operated undercar deluge systems to address such fires.

**Subway Environmental Simulation (SES) Analysis**

A fairly typical tunnel ventilation design has three 100 m³/s fans per station end, with one of the fans being a dedicated standby. The maximum ventilation shaft capacity is thus 200 m³/s with two fans operating.

Having on-board fire suppression systems would eliminate the need to design the ventilation system for an in-train arson fire. The ventilation capacity of the system would then only need to be designed to control a small undercar fire or trash fire.

On this basis, a Subway Environmental Simulation analysis was performed to estimate the necessary fan plant capacity if on-board fire suppression were to be implemented. Cold flow SES simulations were performed at worst case locations within the tunnels. The goal of the analysis was to reach a minimum of 0.76 m/s in the full tunnel area, which is the required air velocity to clear cold smoke.

The analysis showed that the shaft capacity could be reduced from 200 m³/s per ventilation shaft to 100 m³/s per shaft. However, to be conservative pending further detailed analyses, a shaft capacity of 120 m³/s was selected. As per the redundancy criteria, either two 120 m³/s or three 60 m³/s fans would be needed at each station end. The former was selected for this study because it appeared to require less space. As a result, the emergency ventilation capacity at each station is estimated to decrease by 40%.

**RATIONALE FOR AN ON-BOARD TRAIN FIRE SUPPRESSION SYSTEM**

The primary objective of an on-board train fire detection and suppression system is to detect and suppress any interior fire quickly and at the source, while at the same time provide tenable conditions for the passengers on board for as long as it takes to reach a station stop and evacuate the vehicle, particularly when the vehicle is operating in a tunnel.

Currently, a high pressure water mist system activated by smoke detectors provides the simplest, most cost-effective method to meet these objectives. In addition, it provides the following additional fire-life safety benefits over traditional NFPA 130 compliant vehicle interior designs:

- Responds quickly and automatically to any interior fire at the source (less than 60 seconds)
- Reduces fire spread and duration, thus being safer for passengers, as well as providing lower level of damage to rolling stock, stations, right of way and tunnels
- Reduces smoke levels (less smoke inhalation, lower smoke toxicity, reduced level of passenger panic)
- Reduces heat of combustion (suppresses fire, more comfortable for passengers)
- Reduces oxygen level available to fire (suppresses fire) without affecting passengers
- Does not harm passengers or require their evacuation
- Is safe and effective, even for electrical fires
- Is more effective than on-board portable fire extinguishers, which are not always obvious, require passenger application, and may be vandalized or discharged
- Causes virtually no water damage
- Effective even with passenger doors open
- Proven technology – in service on high speed trains for over a decade and more recently on subways in Madrid
- Works in tunnels, stations, at-grade and elevated sections, thus making the entire system safer
- “Targeting” (ensuring the suppressant hits the fire) is not an issue
- Offers the only chance to save lives in an incident car during a major arson event
- Enables fire suppression to begin prior to car windows falling out
- Effective in suppressing multiple fires on one or more trains.

Further, the installation of an on-board fire detection and suppression system can provide the following system support infrastructure benefits while still meeting NFPA 130 requirements:

- Significantly reduces tunnel and underground station ventilation requirements established to deal with burning vehicle smoke and heat release may be possible
- Significantly reduces the impact of designing for fire emergencies on station architecture
- Reduces tunnel ventilation capacities by about 40% per shaft or less
- Reduces the number of tunnel ventilation fans at each end of each underground station, thus saving space
- Requires fewer ventilation dampers
- Eliminates some mid-tunnel shafts
- Enables a time of tenability of 60 minutes to be met during a station fire
- Eliminates the need for downstands
- Eliminates the need for over track exhaust (OTE)
- Decreases shaft airflow areas by about 40%
- Decreases tunnel ventilation shaft grate areas from about 30 m² to about 18 m²
- Although individual tunnel ventilation fan capacity would increase, the fan motor horsepower would be similar and connected loads would be reduced about 40%
- Reduces ventilation equipment high temperature rating requirement from 250°C to 150°C
- Might reduce or delete the need for station sprinklers – a separate study with analysis of combustibles would be needed
- Logic applies to two-bore and one-bore tunnel construction approaches.

Thus, from an overall system fire-life safety perspective, especially where significant parts of the rail system operate in tunnels, it is deemed beneficial to seriously consider the provision of a fully integrated fire detection system coupled with a high pressure water mist fire suppression system to protect passenger areas within the trains.

**TYPICAL TRAINS**

In subway or heavy metro systems, the vehicles are typically heavy rail cars that are semi-permanently coupled into two or more car trainsets. Underfloor equipment is distributed over the cars in a trainset so that they are not identical, although structurally they are the same. For the purpose of illustration, we will consider a typical two-car trainset.
Figure 1: Typical Vehicle General Arrangement

FIRE DETECTION AND SUPPRESSION SYSTEM INSTALLATION ON A TRAIN

Major Elements

The vehicle fire detection and suppression system for a two-car trainset would be designed, supplied and installed as a complete, fully integrated system typically consisting of the following major elements:

- Fire detection and control panel (1 per car / 2 per 2-car unit)
- Smoke detectors (optical type - 4 per car / 8 per 2-car unit)
- Accumulator Unit (1 per 2-car unit)
- Section valves, if required by system design (2 per car / 4 per 2-car unit)
- Spray heads (8 per car / 16 per 2-car unit)
- Ball valves for testing, maintenance, refilling and flushing, including pressure switch (2 per 2-car unit)
- System pipework (including flexible hoses between cars)
- System wiring and cabling.

These listed elements are in addition to all the normal vehicle systems required. For trainsets containing more than two cars, the quantities of additional components would need to be adjusted accordingly.

Fire Suppression System Layouts

There are two basic fire suppression system designs: the standard open spray head arrangement and the pop-out spray head arrangement.

Standard Open Spray Head Arrangement

To date, the majority of fire suppression systems installed on board trains utilize a standard open spray head arrangement. In this arrangement, the passenger area is sub-divided into up to four zones, each controlled by a section valve. When a fire detected signal is given by the fire detection and control panel, the entire system up to all of the section valves fills with water, becoming pressurized. Simultaneously, the fire control panel activates the section valve corresponding to the area where smoke was detected. Water mist is then discharged from all four spray heads in that zone.
A more recent development, the pop-out spray head arrangement uses special pop-out spray heads fitted with heat sensitive quartzoid bulbs. In this system, there is but one passenger area and the section valves are eliminated. When a fire detected signal is given by the fire detection and control panel, the entire system up to the individual pop-out spray heads becomes pressurized and filled with water. All of the pop-out spray heads then pop out and expose their heat sensitive bulbs. When a sufficient temperature is reached to cause a bulb to burst, water mist is then discharged from that individual spray head. Typically, only two pop-out spray heads are activated by the fire. As a result, fewer components and less water are required to provide the same coverage. In addition, the likelihood of a false alarm is reduced due to the combined use of both smoke and heat detection. Only one supplier is currently known to provide this type of spray head.
Physical Location of Equipment

For the purposes of physically locating the fire detection and suppression equipment and ascertaining system equipment weight, the largest and heaviest equipment expected has been used to provide a very conservative evaluation. To maximize competition with potential suppliers, it has also been assumed that the more standard open spray head fire suppression approach would be utilized. It is worth noting that many items of equipment are available in smaller sizes than those presented here, while the choice of a pop-out spray head fire suppression approach will significantly reduce the amount of water necessary to provide protection, greatly reducing both the size and weight of the accumulator unit. However, a conservative total system operational weight of 739 kg is estimated.

Fire Detection and Control Panel

A fire detection and control panel would be provided in each vehicle so as to provide a redundant fire detection system for each car in the trainset. As a separate indication of the overall health of the fire detection and suppression system is to be given in the Operator’s cab, this compact panel does not need to be exposed and can be located behind a locked equipment panel.

The ceiling transition panels between the windows and the ceiling panels where PA speakers, video cameras and other items are typically housed would be an ideal location for the fire detection and control panel and associated power supplies, etc. This location would also simplify the installation of the fire detection system wiring.

Figure 6: Ceiling Transition Panels – Location for Fire Detection and Control Panel and Aspiration Type Smoke Detector Equipment
Figure 7: Typical Fire Detection and Control Panel

Smoke Detectors

The most effective and vandal resistant approach would be to provide four aspiration type optical smoke detectors in each vehicle.

The smoke detector units would be mounted out of sight behind locked panels to avoid potential vandalism. Small diameter nylon tubing would connect each detection unit to a suitable smoke collection point located in the ceiling. Collection points must be as unobtrusive as possible and placed where practicable in difficult to reach areas to prevent any malicious damage / airflow blockage. The final collection point location details would be dependent on vehicle smoke tests.

Figure 8: Typical Aspiration Type Smoke Detector Unit

Accumulator Unit

One accumulator unit that contains the potable water and nitrogen gas bottles necessary for the fire suppression system operation would be provided for each two-car unit. This large and relatively heavy unit is the greatest challenge of all the fire detection and suppression system components to install on the vehicle.
Underfloor mounting of the accumulator unit is preferred to allow easy inspection and periodic draining/refilling of the potable water, but underfloor equipment layouts often leave little free space. Should the system be incorporated on a new build, then a judicious rearrangement of underfloor equipment may still allow installation there.

Other alternative locations include the vehicle roof or under longitudinal passengers seats (in very compact vehicle arrangements where no other possibility exists.)

Section Valves

If a standard spray head arrangement is adopted, two section valves would be provided for each vehicle. These would be located behind a readily accessible end wall panel during pipework installation. Wiring would also be required between these valves and the fire detection and control panel.

Figure 10: Typical Section Valve
Vehicle Interfaces

The most complex part of the installation is the integration of the fire detection and suppression system with the existing vehicle systems to minimize operation and maintenance activities and ensure the new system is in working order at all times. Such integration work requires that fire detection and suppression system engineers work closely together with vehicle specialist engineers in order to establish the detailed modifications to the existing vehicle electrical systems required in order to accommodate the new system. These are primarily electrical in nature (power, signal, control) and will require the installation of additional electrical cabling, connections and components. There are also some mechanical aspects to be addressed.

CAPITAL, OPERATING AND MAINTENANCE COSTS OF ON-BOARD TRAIN INSTALLATION

In a recent study, an Engineer’s Estimate of the capital cost for retrofitting fire detection and suppression systems on an existing fleet of 54 two-car trainsets was found to be on the order of $3,428,000 to $3,646,000 in year 2010. Of this, the major equipment cost would only be around $1,544,400 to $1,755,000 or around $28,600 to $32,500 per two-car unit. For a new build, the total capital cost is expected to be less.

Operational costs are expected to be negligible, although overall energy costs may increase by as much as 1% annually due to the marginally increased vehicle weight.

Although the on-board train fire detection and suppression system is not complex, as a safety critical system, a degree of routine preventive maintenance will be required to ensure it is always ready to be activated. A specialized maintenance team will be required to carry out this work and document that all systems are in proper working order. The additional annual maintenance labor and routine parts costs for 54 two-car trainsets so equipped is estimated to be in the neighborhood of $270,000 to $280,000 per year or around $5,000 to $5,185 per trainset.

SAVINGS IN TUNNEL VENTILATION CONSTRUCTION, OPERATING AND MAINTENANCE COSTS

Construction Costs

If on-board fire suppression systems are installed, the required ventilation equipment capacity would be less, and consequently less space for this equipment would be required in the station boxes. As a result, the typical station box length would decrease approximately 16 m from 206 m to 190 m, and the tunnel length would increase by the same amount. The estimated cost of the station box is $383,172 per meter. The estimated cost of twin-tunnel construction is $41,341 per meter. This would therefore result in an approximate savings of $5,417,620 per station.

A fire emergency situation to avoid is having two or more stopped trains between adjacent ventilation shafts with one of them on fire. Depending on the direction of evacuation selected, the operation of the ventilation system could move smoke from the burning train over the other train, thus harming its passengers. The policy, therefore, is to allow only one train per ventilation zone. However, in some cases, to achieve this, the minimum headway would need to be increased, or mid-tunnel shafts would need to be added to the system to provide additional ventilation zones. If the on-board train fire suppression system was installed, the fire heat and smoke released would be small enough to allow multiple trains within a ventilation zone. In most cases this would eliminate the need for mid-tunnel ventilation shafts, resulting in a savings of $40,000,000.
Equipment Cost

Figures 11 and 12 below show the tunnel ventilation configuration for the end of a typical station with and without on-board fire suppression. There is one ventilation plant room per station end.

The more traditional ventilation design as shown in Figure 11 is based on a standard train without fire suppression equipment and an arson fire: three tunnel ventilation fans are required at each station end. The fans exhaust air from the tunnels and from the station by duct connections that run to the platform and concourse. The concept (ductless OTE/downstand) incorporates a smoke reservoir above the train in the station formed by downstands which run along both tracks. The downstands are mounted to the concourse ceiling above the platform edge and extend to 2.1 m above the platform. For a train fire in the station, smoke is extracted from the reservoirs through openings in the walls at the ends of the platform over each track.

If on-board fire suppression is implemented, as shown in Figure 12, then one tunnel ventilation fan at each end of the station would be eliminated, reducing the number of fans per station from six (6) to four (4). In addition, having on-board fire suppression would eliminate the ductless OTE and downstands, reducing the number of required dampers from 26 to 12 per station.

*Figure 11: Traditional Ventilation Configuration (twin bore tunnel)*

![Figure 11: Traditional Ventilation Configuration (twin bore tunnel)](image-url)
Summary of Construction Cost Savings per Station with Train Fire Suppression

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (in $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station box</td>
<td>5,417,620</td>
</tr>
<tr>
<td>Fans</td>
<td>1,749,531</td>
</tr>
<tr>
<td>Attenuators</td>
<td>359,188</td>
</tr>
<tr>
<td>Dampers and Operators</td>
<td>320,940</td>
</tr>
<tr>
<td>Downstands</td>
<td>211,013</td>
</tr>
<tr>
<td>Emergency Ventilations Shaft Size</td>
<td>120,646</td>
</tr>
<tr>
<td>Ventilation Gratings</td>
<td>18,750</td>
</tr>
<tr>
<td>TOTAL COST Savings Per Station</td>
<td>8,197,688</td>
</tr>
</tbody>
</table>

In one recent study involving seven (7) stations and the elimination of three (3) mid-tunnel ventilation shafts, this approach led to potential savings of $97,383,816.

With a 40% reduction in ventilation requirements, similar savings in operating and maintenance costs would be expected.

CONCLUSION

On-board train fire suppression systems are simple, effective, well-proven and extremely cost effective on any transit system having tunnels and underground stations. Their adoption would further improve life safety and save millions of dollars in construction costs.

REFERENCE LIST

A Comparison of Various Fire Detection Methodologies in Transit Vehicle Fire Protection Systems

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ABSTRACT
Distinctly different fire hazards exist within the engine compartment of a transit vehicle and various detection methodologies may be employed to detect fire events arising from these hazards. The engine compartment presents a particularly challenging environment and it is important to select the correct methodology to ensure timely detection response in the early stages of the development of a fire whilst minimizing nuisance alarms. This paper presents experimental data to demonstrate the variation in the response times of different detection methodologies in the presence of common fire events in the form of simulated flaming fuel fires and a simulated electrical fault in the form of an overheated electrical cable. The data presented relates to experiments conducted within a simulated transit vehicle engine compartment and includes the impact of environmental parameters, such as cooling due to high airflow rates, on detection response times. The paper will conclude with the lessons learned from this testing, and provide insight into key aspects for successful detection of the different fire hazards in this demanding application.

KEYWORDS: engine compartment, fire, detection, response time

INTRODUCTION
A large percentage of reported transit vehicle fires originate in or around the engine compartment. One study conducted in Finland suggests that over 64% of fires originate within the engine compartment [1]. Another study conducted by NFPA suggests that over 64% of transit bus fires originate from within the engine area, running gear or wheel area of the vehicle [2].

In an FMCSA commissioned study 83 fire events are directly attributed to specific fire ignition points within the engine compartment [3]. Of these 83 events, 53% were identified as fast flaming fires originating at the turbo charger or fluid lines, and a further 20% were directly attributed to electrical faults within the engine. This allows engine fires to be broken down into two distinct classes of fire threat. The first class is fast flaming fires resulting from ignition of flammable liquids. The second class is slow growth fire events arising from electrical faults.

For on-board fire protection systems, the time taken to detect the fire event is a critical factor in ensuring the expedient evacuation of passengers and minimising damage to the vehicle [4]. Faster detection of a fire allows for the deployment of an extinguishing agent in the early stage of development of the fire, which increases the likelihood of successfully extinguishing/suppressing the fire whilst it is still a small event. It has been suggested that the choice of detection methodology may result in a variation in response times from 0.1 seconds to 180 seconds [5]. The choice of the detection methodology is therefore an important consideration.

The aim of the experimental work described in this paper was to provide a side by side comparison of the response times of several fire detectors when subjected to flaming fuel fires and electrical faults. Two distinct sets of experiments were carried out within the test article to address the two distinctly different classes of fire threat. The first set of experiments aimed to provide a comparison of the
response of the detectors under test to fast flaming fires arising from the combustion of flammable liquids within the engine compartment. The second set of experiments aimed to provide a comparison of the response of the detectors under test to overheat/fires associated with electrical faults.

It is hoped that the results of this experimental work may provide an improved understanding of the relative performance of the commonly employed detection methodologies. From this improved understanding some conclusions can be drawn regarding the appropriate choice of detection methodology for fire detection within a transit vehicle engine compartment.

This paper concentrates on the performance of detection methodologies with respect to the detection times in the presence of common fire threats. In addition to detection times, both the initial installation cost and ease and cost of maintenance are also important factors which must be taken into consideration when selecting a fire protection system. To some extent both the initial installation cost and ease and cost of maintenance are dependent upon the system supplier and exact details of the integration of the system. As such only the relative cost of individual detectors has been considered. Any further discussion on cost of installation and ownership of an automatic fire detection system is considered to be beyond the scope of this paper.

**DETECTORS TESTED**

Only two basic detection methodologies are recommended for fire detection within transit vehicle applications; thermal detectors, both spot thermal and linear heat detectors, and optical flame detectors [6]. The choice of detectors aimed to encompass these three broad categories of detection methodologies. Details of the different types of detectors available in each of these categories, their operating principles and suitability for engine compartment applications have been discussed elsewhere by the authors and others [7],[8],[9],[10].

A summary of the detectors included in these tests and the identification for each alarm temperature threshold are shown below in Table 1. The exact choice of fire detectors was driven by the ease of availability of devices at the time of testing. The devices chosen are currently utilised in vehicle applications and are designed to withstand the harsh environment of a transit vehicle engine compartment. Specifically, these devices are specified to operate over an ambient temperature range of -40°C to 125°C, withstand the shock and vibrations encountered within vehicle applications and are rated as NEMA 4X enclosures.

Three relatively low cost spot thermal detectors were evaluated. These were fixed temperature normally open thermostats of a bimetallic snap disc construction. The chosen alarm temperatures for the spot thermal detectors were 140°C, 177°C and 232°C.

A dual infrared optical flame detector was evaluated. The chosen optical flame detector is specified by the manufacturer to be suitable for the detection of liquid fuel fires up to a distance of approximately 1070mm. This specification is based upon the detection of a 300mmx300mm pan fire within a 100° field of view. The manufacturer also claims that the detector is immune to false alarms from sunlight, flashlights, lightning, vehicle headlights, incandescent lights and welding arcs. In addition, the manufacturer’s claims suggest that this device is able to operate even when heavily contaminated by oils and other fluids.

Two types of linear heat detector were also evaluated. The first type of linear heat detector employed in these tests was a relatively high cost “averaging type” detector comprised of a pair of conductors separated by a negative temperature coefficient semiconductor material [11]. Due to the averaging nature of these linear heat detectors, different length elements will exhibit different response characteristics for a given overheat/fire event. As such the decision was taken to include both a 1700mm length element and a 6000mm length element in the comparative tests. Two alarm temperature thresholds were set for each averaging linear heat detector element, the first at 125°C and the second at 180°C. The alarm temperature threshold corresponds to the impedance of the element when fully immersed at the specified temperature.

The second type of detector employed was a relatively low cost, discrete alarm temperature linear heat detector. The construction of this device is a twisted pair of conductors separated by a polymer
insulator. This polymer softens and melts above the alarm temperature causing the conductors to be brought into contact, closing an alarm circuit. This is a single use device which cannot be reset and must be replaced after alarm. The chosen detector is specified with a 176°C alarm temperature.

Table 1: Summary of detectors employed during flammable liquid fire tests

<table>
<thead>
<tr>
<th>Detector Identification</th>
<th>Alarm Temperature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 1</td>
<td>125°C (257°F)</td>
<td>1700mm length of averaging linear heat detector</td>
</tr>
<tr>
<td>Average 2</td>
<td>125°C (257°F)</td>
<td>6000mm length of averaging linear heat detector</td>
</tr>
<tr>
<td>Average 3</td>
<td>180°C (356°F)</td>
<td>1700mm length of averaging linear heat detector</td>
</tr>
<tr>
<td>Average 4</td>
<td>180°C (356°F)</td>
<td>6000mm length of averaging linear heat detector</td>
</tr>
<tr>
<td>Discrete</td>
<td>176°C (349°F)</td>
<td>1500mm length of discrete linear heat detector</td>
</tr>
<tr>
<td>Spot 1</td>
<td>140°C (280°F)</td>
<td>Snap disc spot thermal detector</td>
</tr>
<tr>
<td>Spot 2</td>
<td>177°C (350°F)</td>
<td>Snap disc spot thermal detector</td>
</tr>
<tr>
<td>Spot 3</td>
<td>232°C (450°F)</td>
<td>Snap disc spot thermal detector</td>
</tr>
<tr>
<td>Optical</td>
<td>N/A</td>
<td>Dual infrared optical flame detector</td>
</tr>
</tbody>
</table>

FLAMMABLE LIQUID FIRES

The test article employed for the comparison of the detector response times to flammable liquid fires was based around the enclosed chamber shown in Figure 1. This has a free volume of 3600litres to which a variable airflow from 0litre/sec up to 1950litre/sec may be applied. The free volume of the enclosed test chamber is consistent with reported rear mounted engine compartment volumes of 3000litres to 4000litres [12]. By extrapolation of published data relating airflow rates to engine running speeds, the maximum airflow rate of 1950litre/sec is believed to be equivalent to an engine speed of 2200RPM (revolutions per minute) [13]. This represents an average running speed for a transit bus engine. Similarly an airflow rate of 980litre/sec is believed to be equivalent to an engine speed of 1100RPM, which represents a fast idle of the engine.

Three fire pan sizes were used for the tests. These were square fire pans with dimensions 200mmx200mm, 300mmx300mm and 400mmx400mm, each approximately 100mm in height. These were filled with water up to approximately 25mm from the top of the pan (the water was replaced before each test). 0.5litres of diesel was added to the 200mmx200mm and 300mmx300mm fire pan and 1.0litres of diesel to the 400mmx400mm fire pan. Fifteen 0.5mm diameter metal sheathed type K thermocouples, labelled T1 to T15, were installed in the test chamber, as shown in Figure 1.

The spot thermal detectors were installed approximately 300mm below the ceiling of the test chamber and positioned directly above the centre of the fire pan location. Approximately 1500mm lengths of each linear heat detector were installed at the same height along the length of the chamber. Any excess length of the linear heat detector was placed in the enclosure above the roof of the test chamber. An optical flame detector was installed 850mm horizontally from the centre of the pan. The height of installation of this detector was adjusted to ensure that the centre line of the detector was approximately 300mm above the top of the fire pan.

A number of tests were carried out with each size of fire pan placed either 500mm or 1000mm below the detectors. The alarm output from all detectors and the temperature measured by the thermocouples were recorded at 0.5second intervals. From this data the time to alarm was calculated by identifying the point of ignition from the data recorded by a thermocouple installed at the edge of the fire pan.
Figure 1 – Configuration of test article employed during flammable liquid fire tests

The full data set relating to the response times to flammable liquid fires is presented graphically in Figure 2 to Figure 7. The full temperature profile obtained 1000mm above a 400mmx400mm diesel pan fire with airflow through the chamber of 0litre/sec and 1960litre/sec is also shown in Figure 8.

Analysis of all response time data suggests that the response time of the optical flame detector is unaffected by the airflow rate and should also be unaffected by distance, providing it is correctly installed with an unobstructed view of the fire source within the manufacturer’s specified field of view and detection distance. In contrast to optical flame detectors, increasing either the airflow rate and/or distance between the detectors and the fire results in increased response times for the spot thermal detectors and linear heat detectors.

It therefore follows that a reduction in response time will be achieved by locating any heat detectors
as close to the source of fire as practically possible. Due to the nature of the fire threats it is generally necessary to locate heat detectors in the vicinity of known hot surfaces within the engine. In this case it is important to consider the possibility of nuisance alarms. Setting the height of heat detectors is therefore a balance between minimising the response time whilst ensuring sufficient immunity to nuisance alarms.

The variation in the temperature across the chamber due to differing airflow rates is highlighted by the temperature profile shown in Figure 8. These results highlight the fact that a spot thermal detector or linear heat detector positioned so that it experiences a temperature sufficient to generate an alarm with no airflow present may not necessarily experience a similar temperature when the airflow through the engine compartment is increased.

The influence of an increased airflow rate on the response time of the thermal elements is due to both the cooling effect of the flowing air and displacement of the flame by the airflow. When airflow is introduced the flame is displaced horizontally and this, in combination with the cooling effect of the flowing air, reduces the rate of rise of temperature at the position of the detectors. The slower rate of rise of temperature results in a slower speed of response.

A comparison of the response of all linear heat detector elements suggests that averaging type linear heat detectors with a lower temperature alarm (125°C) provide a similar response to a discrete linear heat detector with an alarm temperature of 176°C. This suggests that the averaging nature of this sensing element will reduce its sensitivity to localised heating. It should be possible to take advantage of this and, through careful consideration of the exact installation position, place the averaging linear heat detector closer to known “hot spots” than would be possible with a discrete linear heat detector.

At the same time, this approach would allow a reduction in the average alarm temperature employed to monitor the cooler regions of the engine. This approach has been common for some time within the aerospace industry and there is no reason why a similar approach could not be successfully applied to transit vehicle engine compartments [11].

Finally we must consider the relative cost of the detector elements. Spot thermal and discrete linear heat detectors are the simplest and lowest cost solution. The use of averaging type linear heat detectors may offer an attractive medium cost alternative. Optical flame detectors are the highest cost option. The cost of the detection methodology must however be considered in light of the potential cost of damage to the vehicle. It is likely that the slower response time of heat detectors will lead to greater damage to the vehicle than would have been the case with optical flame detectors and this should be kept in mind when making a choice between different detection methodologies.

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Figure 2 - Response time from point of ignition with all thermal detectors positioned 500mm above a 200mmx200mm diesel pan fire. Where no time is indicated the detector failed to produce an alarm.
Figure 3 - Response time from point of ignition with all thermal detectors positioned 500mm above a 300mmx300mm diesel pan fire.

Figure 4 - Response time from point of ignition with all thermal detectors positioned 500mm above a 400mmx400mm diesel pan fire

Figure 5 - Response time from point of ignition with all thermal detectors positioned 1000mm above a 200mmx200mm diesel pan fire. Where no time is indicated the detector failed to produce an alarm.
Figure 6 - Response time from point of ignition with all thermal detectors positioned 1000mm above a 300mmx300mm diesel pan fire. Where no time is indicated the detector failed to produce an alarm.

Figure 7 - Response time from point of ignition with all thermal detectors positioned 1000mm above a 400mmx400mm diesel pan fire. Where no time is indicated the detector failed to produce an alarm.
ELECTRICAL FAULTS/FIRES

A comparison has been made of the response time of all detectors in the presence of overheats/fires associated with electrical faults. In this case the response time of the detectors from the point of initiation of the electrical fault was considered. This comparison was conducted with the experimental apparatus installed in the same test chamber utilised for flaming fuel fire and modified as shown in Figure 9. This experimental setup simulates an electrical short by connecting an 1800mm length AWG6 electrical cable across 2 x 12V 110AH automotive lead acid batteries connected in parallel. When fully charged each battery is capable of supplying 750CCA (cold cranking amps).

The cable under test was installed approximately 200mm above the floor of the test chamber and the linear heat detectors were installed along the length of this cable, with a standoff distance between the cable and the elements of approximately 10mm. The spot thermal detectors were installed 900mm from the end of and approximately 10mm below the cable under test. Three optical flame detectors were also installed. These were positioned to provide full coverage of the cable. The temperature along the length of the cable under test was monitored with six equally spaced 0.5mm diameter metal sheathed type K thermocouples, labelled T1 to T6. These thermocouples were clamped to the cable. The alarm output from all detectors and the temperature measured by the thermocouples were recorded at 0.5second intervals.

The response time data for electrical faults are presented graphically in Figure 10. A typical temperature profile for an AWG6 cable subjected to a short is also shown in Figure 11. A short will result in significant heating causing the cable to reach temperatures in excess of 600°C. This results in thermal decomposition and pyrolysis of the cable coating. Due to the presence of flame retardants in the polymer coating, open flaming will not always occur and when it does these are small transient events.

Figure 8 - Temperature profile 1000mm above a 400mmx400mm diesel pan fire measured by the thermocouples positioned as shown in Figure 1. (a), (b), (c) without airflow. (d), (e), (f) airflow=1960litre/sec.
The time response data highlight the fact that optical flame detectors are not suitable for the detection of these types of electrical faults due to the non-flaming nature of these events. The data presented also suggest that spot thermal detectors are an unreliable method of detection for these faults. The failure of the spot thermal detectors is likely to be due to a combination of the uneven, localised heating of the cable and the relatively large thermal mass of the detector. The effect of localised heating is common to all spot thermal detectors irrespective of the mode of operation. It may be possible to address the issue of the large thermal mass associated with discrete spot thermal detectors by utilising rate of rise devices; however the increased susceptibility to false alarms must then be considered. It is also important to bear in mind that a fault can occur at any point along the cable. The correct location for any spot thermal detector is therefore difficult to predict.
Linear heat detectors represent the most suitable and reliable detection methodology for fire events initiated through electrical faults. During the test described a standoff distance of 10mm was maintained between the electrical cable and the linear heat detector. The detection times shown therefore represent values somewhat slower than may be achieved in a practical installation if linear heat detectors are placed in closer proximity to cables.

The discrete linear heat detector and the shorter lengths of averaging linear heat detector appear to provide a consistent detection performance regardless of the level of airflow through the test chamber. By contrast the longer lengths of averaging linear heat detector display degradation in detection performance at the highest airflow rate of 1950 litre/sec. This result may be understood by noting that the shorter length averaging element will experience heating from the cable along the whole length of the element, whereas with the longer length only a fraction of the element will be heated. The heated section of the longer length element must therefore reach a higher temperature to generate an alarm. This makes it more susceptible to the cooling effect of fast airflow.

![Figure 10 - Response time from point of initiation of electrical fault for all detectors. Where no time is indicated the detector failed to produce an alarm](image1)

![Figure 11 - Temperature profile along a 1800mm length of AWG 6 electrical cable from the point of initiation of a 12V short, as measured by the thermocouples along the length of the cable](image2)

**SUMMARY/CONCLUSION**

The results from a side by side comparison of the response times of the main classes of detectors utilised in transit vehicle engine compartment applications when subjected to flaming fuel fires and electrical faults has been presented. The contrast between the response times of the different detection methodologies for flaming fires and electrical faults highlights the need to match the detection methodology to the perceived fire threat. The contrast in response times also suggests that a
solution that provides the fastest and most reliable detection response may be a combination of optical flame detectors and linear heat detectors to address the distinctly different fire threats that exist within a transit vehicle engine compartment.

The key points relating to the detection methodologies recommended for fire detection within transit vehicle engine compartment applications are summarised below:

Optical flame detectors provide the fastest response to a flaming fuel fire and are the least affected by varying airflow rates. In situations where a flame detector may be positioned with an uncluttered FOV covering the zone of concern this overcomes the risks of potential gaps in coverage associated with heat detectors. It is important however to bear in mind that optical flame detectors require a clear view of the area of concern and may not always be a suitable choice due to this fact. Optical flame detectors are also unsuitable for the early detection of the slow smouldering non-flaming events that arise from electrical faults. In this case linear heat detectors provide the fastest response.

The usefulness of spot thermal detectors is limited, particularly with respect to the detection of electrical faults. The use of linear heat detectors is the preferred option for the detection of electrical faults. In addition linear heat detectors by nature of their design readily lend themselves to an installation that ensures full coverage of the area surrounding potential fire hazards and are the preferred heat detection approach for all fire scenarios. The response of all heat detection elements is however strongly influenced by both the installed location and air flow. As such, careful design of the installation position for heat detectors is required, based upon knowledge of the location of the potential fire threats.

The use of averaging type linear heat detectors may offer an attractive medium cost alternative to optical flame detectors. It should be possible to take advantage of the averaging nature of these devices and, through careful consideration of the exact installation position, place the averaging linear heat detector closer to known “hot spots” than would be possible with a discrete linear heat detector. It is likely that the slower response time of heat detectors to flaming fires will lead to greater damage to the vehicle than would have been the case with optical flame detectors and this should be kept in mind when making a choice between these two methodologies.

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Developing a fire resistance test for vehicles with rechargeable energy storage systems

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ABSTRACT
Vehicles with electric drive are a promising solution to meet the requirements set up to reduce the climatic load from the transport sector. While these vehicles differ significantly from other vehicles in many aspects such as voltage levels and energy storage it is important to determine safety requirements in an early stage before the market penetration is large. To this end work was started in late 2010 in an informal group of interested experts to make suggestions for an amendment of UNECEs Regulation 100. One requirement that has been developed there is a Fire resistance requirement.

KEYWORDS: Electric drive, fire resistance, Rechargeable Energy storage systems

INTRODUCTION
Vehicles with electric drive are a key solution for reducing the release of global warming gases from the transport on roads. In order to facilitate a smooth introduction of these to the market it is important to have regulations available to ensure that these vehicles are as safe as traditional vehicles. Work started to define such requirements in an informal group of interested experts which reports to GRSP of UNECE. The work started in the end of 2010 and a suggestion for requirements was submitted to GRSP in May 2012. The document was received well by GRSP and was the secretariat of the group of experts was requested to submit the proposal to WP.29 and AC.1 for consideration and vote at the November 2012 sessions [1].

The proposal that was prepared included requirements for:
- Vibration
- Thermal Shock and cycling
- Mechanical Impact
- Fire resistance
- External short circuit protection
- Overcharge protection
- Over-discharge protection
- Over-temperature protection
- Emission

SP was asked to write a first proposal for a Fire resistance test based on R34. This poster presents the experiments that were conducted in order to write this proposal and also gives an update on changes made in the final proposal.

FIRE RESISTANCE TEST ACCORDING TO R34
Plastic fuel tanks are tested against a fuel fire for a total of 2 minutes according to R34. The tank is not allowed to leak during and after the test. The tests are conducted using commercial fuel in a pool exceed the horizontal projection of the tank by at least 20 cm, but not more than 50 cm. First the fire is ignited away from the vehicle and after 1 minute preheating time the fuel fire is then placed underneath the vehicle. The fire continues for 1 minute before bricks are placed in the pool that reduces the fire. This reduced fire continues for 1 minute before it is removed from the vehicle.
TESTS IN PREPARATION OF PROPOSAL

In order to draft a proposal for a fire resistance test for REESS some aspects of the tests in R34 were investigated. These were:

- The influence of using a pre-heating time or not. This is interesting as battery packs will be distributed over a large area of the vehicle and moving a large pool filled with burning fuel is difficult without risking spills.
- The influence from different fuels i.e. summer and winter quality of petrol.
- The influence of different exposure times (direct and indirect exposure) as being able to conduct the tests without the indirect exposure would make the test easier to conduct.
- Difference in exposure between Heptane and petrol as Heptane is more worker friendly and a fuel with stable properties often used in fire testing.
- What height above the fuel should one place the REESS in a component based test. The experience from R34 testing is that the height above the fuel will influence the results significantly.

Three test series were conducted to investigate this:

- One series on a mock-up chassi, varying fuel, pre-heating time, direct exposure time and indirect exposure time. Tests were conducted to evaluate different procedures.
- One series where the temperature above pool and Heat Release Rate was measured. The tests were conducted using different fuel (winter and summer 98 octane petrol and Heptane).
- Temperature as a function of height above fuel. Tests were conducted to establish suitable placement for a RESS in a component test.

RESULTS

Seven tests were conducted on the mock-up chassi:

- Test 1 swedish winter petrol, normal R34 procedure
- Test 2 same as test 1
- Test 3 winter petrol, no pre-heating, 90 s direct exposure (without bricks), 60 s indirect exposure (with bricks)
- Test 4 winter petrol, no pre-heating 60 s direct exposure, 60 s indirect exposure
- Test 5 winter petrol, no pre-heating, 120s indirect exposure with bricks in place entire time, no cooling afterwards
- Test 6 repetition of test 1
- Test 7, Heptane, normal R34 procedure

Heat Release rate was measured in all tests together with the temperature at 5 places of the mock-up chassis. The results from the temperature measurements are presented in Figure 1.

![Figure 1. Mean temperatures on Mock-up chassi in test1-7](image-url)
Based on these results the following conclusions were made:

- Preheating makes some difference, the influence might be larger if the fuel is not kept at RT before ignition
- There is a stochastic variation in exposure, suggest to increase direct exposure by 10 s to compensate for this and the exclusion of preheating
- Cooling afterwards influences the result, but it is not a realistic scenario – suggested that it should be removed based on this
- Having the bricks in place from the beginning, i.e indirect exposure during entire time, results in a slower heating but the end temperature is about the same as in the normal procedure, suggested to retain heating with and without screen

Four tests were conducted to investigate the influence of fuel.

- Test 8 Swedish Winter Petrol
- Test 9 Same as test 8
- Test 10 Heptane
- Test 11 Swedish Summer Petrol

The Heat Release Rate was measured in all tests together with temperature readings from three plate thermometers placed above the fuel surface as shown in Figure 2.

![Figure 2. Placement of Plate thermometers in Test 8-11](image)

The results as shown in Figure 3 the conclusion to keep the commercial fuel.

![Figure 3. Mean Plate thermometer temperature in test 8-11](image)
Five tests were conducted using different pool sizes with diameters ranging from 0.5 metres up to 1.7 m. Temperature readings were recorded every 10\textsuperscript{th} centimetre above the fuel surface in the tests, an example of results is given in Figure 4. Based on the results it was concluded that a suitable height above the fuel for a component test is 50cm.

![Figure 4. Example of results from tests conducted in order to determine a suitable height above the fuel in component based tests.](image)

**CONCLUSIONS**

Based on the test results a proposal for the test procedure was written. It was proposed to omit the preheating phase if one could ensure the fuel temperature before test. In addition, it was decided to use petrol and not Heptane and a suitable height above the pool in a component based test would be 50 cm. This proposal was included in the current suggested amendment on UNECE Regulation 100 [1]. Since the tests and the first proposal, changes have only been made in terms of temperature of fuel needed in order to omit the preheating phase, ambient temperature, conditioning of test object and acceptance criteria.

**REFERENCES**

Extreme duty fire products improve vehicle protection.

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CONTENT:
New fire challenges are all around us. Nowhere is this truer than in the extreme environments created in the world of professional racing and military. TPR², A fire technology company in Essex, CT, has been redefining extreme fire solutions at breakneck speed since it’s inception in 2004 when, in 2 months, it created an innovative chemical resistant, ductile fire coating for the Milliken ballistic panel and Dow IMPAXX® foam in the NASCAR® Car of Tomorrow.
In TPR²’s world, Extreme situations often exist where normal or ‘over the counter’ fire solutions will not work. New technologies TPR2 already uses in these environments could have significant impact on the vehicle world such as the ones in FIVE. This abstract will go through a recently released range of viable inexpensive technologies that exist at TPR² and can be readily used in FIVE type vehicles.

Game changing benefits:
Many of TPR2 products have been invented to overcome environmental conditions that plague other intumescent and fire protective products. The chart below enumerates the broad breadth of capabilities of our coating lines…

TPR² coatings can be adjusted to perform in different conditions. These ‘Smart’ products can change characteristics at specific temperature ranges.
The chart below enumerates characteristics we can modify to optimize an extreme duty coatings performance:

TPR²’s fire protective, non-flammable coatings in use today also extinguish liquid fires, block vapor fires, and even mitigate blast heat. They have been accredited as ‘fire extinguishing’ by SFI, The international professional racing accreditation body, as well as a fire barrier intumescent. They are waterbased, without VOC issues or any harmful solvents.

SFI International exists solely to mandate safety worldwide in all phases of racing including Formula 1, NASCAR, NHRA, IHRA, speedboats, monster trucks, and BAJA. SFI 54.1, a fire protection specification for all plastic, composite and flexible tubing, defined rigorous, aggressive standards to protect drivers and vehicles from explosions, flame fronts, liquid fires, and vapor fires. TPR²’s TEMPROTEX® coatings are the only products which passed the tests, which include:

**THERMAL AND FLAME BARRIER PERFORMANCE OVER COMPOSITES**
- The after-flame time shall be fifteen seconds or less. Additionally, no flare up in the presence of the torch, no reigniting and no burn through of the panel may occur. Any one such occurrence shall be considered a failure

**LIQUID FIRE EXTINGUISHING PERFORMANCE OVER COMPOSITES**
- The burning oil shall extinguish within fifteen seconds of being poured onto the panel. After 30 seconds any remaining oil shall not reignite on the panel nor should the panel surface ignite. Any one such occurrence shall be considered a failure.

**VAPOR FIRE - THERMAL AND FLAME RESISTANCE**
- During the test, the sample panel shall not ignite. Immediately after the methanol burns off, the coating shall be intact on the panel surface. Upon cool down of the panel (at least 10 minutes), the coating shall be intact on the panel surface. Any one such occurrence shall be considered a failure.

TPR² has had similar success with other common vehicular components it has worked on.
Foams/fabrics/blankets:
“FOAM that meets 10 minutes fire tests”

Besides intumescing weatherproof fire coatings, fire extinguishing and fire barrier coatings, TPR² has developed fabrics, foams and blankets which can withstand common vehicle conditions and provide new levels of fire safety. New, highly flexible, moisture resilient, fire protective and fire barrier saturants & coatings are being used with a variety of Polyether foams, fabrics and ticking. Fire results are achieving new standards for fire resistivity. The foams have already passed rigorous fire tests for prisons, dragsters, military helicopters, and naval vessels. The saturants have been used to treat foams and creat low cost, fireproof cushioning and structural foams. These foams have proven fire ratings that far exceed current MVSS & FAR standards. Foams are currently in use that can absorb oil without letting it ignite, block metal sparks and slag and extinguish burning embers. Fire resistance credentials include UL94 V0, ASTM E84, and ASTM E136(10 min fire) class A ratings. Fire barrier blankets and fabrics have been produced which can contain 1” molten weld slag, extinguish liquid fires and absorb blast heat. Treated nylon and PE films have passed UL94, MVSS 302 and FAR 25.853 tests.

Composite/Thermoset plastics:
“Fireproof composites and thermosets at minimal cost increase”

TPR² treated fiberglass, epoxy, composite and potting compounds tested to ASTM E84/UL 723 flame and smoke are now available. Some thermosets actually increased in compression strength beside becoming Fireproof. Many of these NEOplastic™ products come with minimal cost increase. NEOplastic™ polyester resin has already achieved a Class A(<25fs, <50 smoke) fire rating.

As a secondary approach (in many cases for retro or renovation/recall fixes), TPR² coatings over the same composites and thermoset plastics also achieve unparalleled fire endurance. This, combined with the coatings excellent wear resistance, waterproof capabilities, extreme ductility, and green environmental impact, could be excellent new technologies for many vehicular applications.

Also in racing, the TPR² coatings have been used to visually identify borderline unsafe temperatures which might be unnoticed with current safety technologies (think color changing paint but for use in 300-450 f range) as well as being used as sacrificial coating… providing protection in catastrophic events (such as for explosions in NHRA dragsters carbon fiber bodies and components). Some products have been used to identify areas where temperatures approach known critical limits by phase changing into a fire barrier or heat barrier when critical limits are exceeded.

Below is the phase change SFI credentials for TPR² Temperotex® race coating:

HEAT INSULATING PHASE:
A) At normal performance temperatures (metal up to 250f ongoing):
TPR² Coating will keep IMPAXX™ foam below 200f and keep MFT™ and thermosets from reaching softening temps. Coating will maintain its adhesion, water resistance and fire extinguishing characteristics.

B) At ‘Runaway’ Heat Conditions (250f-400f):
TPR² Coating will insulate substrate during spikes of heat over 250f. The coating will sacrificially insulate but will blister with continuous runaway temperatures. With sustained runaway temperatures, the MFT™ will eventually delaminate upon itself. Blistered coating is a sign that temperatures are consistently above NASCAR expectations and should be addressed. Thermoster plastics (CF, fiberglass), could darken and deform possibly.

C) At Catastrophic Heat Events (400+f):
TPR² Coating will support short heat bursts into the catastrophic range when applied to IMPAXX™, MFT™ and Thermoster plastics. Any catastrophic heat seen for more than 5-10 minutes will melt the IMPAXX™ or MFT™. 800+f temps could generate enough
calories of heat to combust under the coating. Temprotex™ coating helps extinguish combusting molten plastic, foam and thermosets, and significantly reduce smoke generation.

FIRE BARRIER PHASE:
A) At Continuous Performance Temperatures (metal to 250f ongoing),
B) At 'Runaway' Heat Conditions (250f-400f), or
C) At Catastrophic Heat Events (400+f):
  Coating will keep a flame from both MFT™, thermosets and IMPAXX™ to standards set forth in UL 94. The coating's protective performance has passed UL 94's highest flame retardant rating(V0) over MFT™ and IMPAXX™ in test recreations. Any fire exposure would be classified as catastrophic and all components should be replaced.

NON FLAMMABLE PHASE:
A) At Continuous Performance Temperatures (metal to 250f ongoing),
B) At 'Runaway' Heat Conditions (250f-400f), or
C) At Catastrophic Heat Events (400+f):
  Coatings will not combust nor support combustion.

ALL PHASE FIRE EXTINGUISHING REQUIREMENTS:
A) At Continuous Performance Temperatures (metal to 250f ongoing),
B) At 'Runaway' Heat Conditions (250f-400f), or
C) At Catastrophic Heat Events (400+f):
  When splashed with flaming liquids, even at elevated temperatures, the coating will consume copious amounts of heat energy. It will bring and maintain fuel source below flash point and delay the heat from wicking to the substrate.

When you overlay these revolutionary performance characteristics with features such as weatherability, chemical resistance, ductility, Green, LEED capable, SQAMD approved, mold resistance, food grade capability and exterior grade, the commercial and industrial market opportunities become endless.

Tests passed include:
UL 94 Vo
MVSS 302
FAR 25.853
Boeing BMS 10-117
ASTM E162 with treated foams of multiple types and densities
ASTM E84/UL723 with treated foams of multiple types and densities, Plastics, Composites
SFI 54.1
ASTM E84 (extended) ‘non combustibility’ with coatings
NFPA 286 full scale 15 minute over composite fiberglass/foam panels
ISO 21487/ABYC H33 fuel tank fire & static pressure test over fiberglass composite tanks
EPA Method 24
ASTM E 96 vapor barrier
USDA FSIS incidental food contact regs
ASTM D 3273 degree of mold resistance test of coatings
Wind driven rain, heat aging and ductility testing
Chemical resistance testing

As with many of our revolutionary fire technologies, TPR² can modify these new products to adapt to various tests. There are many unserved applications that are just ‘a fire test away’. They would require funding, focus and open partnerships; all of which TPR2 is interested in participating in at confidential level or open relationships.

These emerging products can offer broader application solutions for a vehicle’s environmental challenges while still offering new levels of fire protection.

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WHO IS PINFA?

PINFA is the non-halogenated Phosphorus, Inorganic and Nitrogen (PIN) Flame Retardants Association and is a Sector Group of Cefic, the European Chemical Industry Council. Created 2009 by 6 companies, it today gathers 20 producers and users of non-halogenated FRs.

It has also agreed mutual membership with iNEMI (International Electronics Manufacturing Initiative), a major industry organization globally active in the field of electronic products, and talks are ongoing with other industry organizations, which are expected to result in new memberships and agreements in the coming months. Further membership with any company or organization having stakes in flame retardant products or fire safety issue is welcome.

WHY FLAME RETARDANTS?

The need for high fire safety requirements in transportation has been well exposed and discussed during the 1st FIVE conference in 2010, in particular regarding the specifications that are valid for road vehicles (cars, buses), which can be regarded as obsolete today. With the anticipated increased use of plastics and natural fibres (light-weight construction, fuel savings), the multiplication of onboard electronics (GPS, DVD etc) and related cabling, along with the upcoming move towards electro-mobility fires in cars are not expected to decrease, unless specifications would be upgraded.
While many papers in Gothenburg compared the fire performance of materials used i.e. in trains or airplanes (well regulated areas) versus those used in cars and busses (less stringent), little has been said on how to achieve such high a level of fire safety. Apart from using inherently less flammable materials (which normally more expensive, and sometimes heavier), the use of flame retardants (FR) is a viable option to prevent fires from happening, and is thus totally complementary to smoke/fire detection and active fire fighting techniques when considering a full-system approach.

WHAT ARE FLAME RETARDANTS?

The term “Flame retardants” describes the function of these additives, but says nothing about their nature, their properties nor about their mode of action.

FRs can be organic or inorganic, liquid or solid, and one can further differentiate between additive FRs (just are physically blended with the substrate) and reactive FR, which undergo a chemical reaction with the substrate or become part of the polymer.

FRs can be classified into different families based on their chemistries:
- brominated FRs
- chlorinated FRs
  Commonly referred to halogenated FRs. Iodine or fluorine derivatives, although being also halogens, are too stable to be used as FRs and thus do not fall under this definition.
- phosphorus FRs include different oxidation stages of the P elements, i.e. phosphates/polyphosphates, phosphonates, phosphinates, phosphine oxides, red phosphorus
- nitrogen based FRs: include mainly melamine derivatives, but also other nitrogen compounds, such as guanidine or other triazine compounds.
- inorganic FRs include a variety of chemicals, incl. metal hydrates (ie. Aluminium trihydrate/ATH, Magnesium Hydroxyde/MDH), antimony oxides (synergist to halogen sources), borates, clays, stannates and few others.

Certain FRs can have one or several of the a.m. elements on their backbone, i.e. chlorine and phosphorus, phosphorus and nitrogen etc. In total, there are more than 170 substances which can act as FRs. Very often, combinations of two or more FRs are used in order to achieve synergistic effects (where the combination is more effective than the single FRs) and/or optimize processing and/or obtain a certain set of properties (i.e. physical properties of the treated article) and/or to optimize the costs of the formulation.

PINFA exclusively represents FR technologies based on non-halogenated phosphorus, inorganic and nitrogen chemistries.

WHAT IS THE ROLE OF FLAME RETARDANTS?

Fire can be defined as an uncontrolled combustion. Combustion is a complex chain reaction that, according to Emmons’ fire triangle, requires three conditions to be given at once: fuel, oxygen and heat. If one of these parameters is interrupted or is disturbed enough, the combustion will stop.

FR do not make flammable materials non-flammable. What all FRs have in common is that they will increase the energy required to ignite a material and will slow down or interrupt the combustion process. This will be achieved by influencing one or more of these three parameters of the fire triangle, which in turn, is dependant of the chemistry and inherent mode of action of the FR(s) used.
HOW DO PIN FLAME RETARDANTS WORK?

PIN FR develop their FR effect through different mechanisms, either through chemical reactions, physical effects or through a combination of both. These complex, sometimes polymer-specific reactions can take place in the solid (or condensed) phase, and/or in the melt and/or in the gas phase.

1) chemical action in the gas phase
This typically applies to halogen FRs, which release acidic gases (HBr or HCl) that will interact with hydrogen radicals in the flame through radical activity.

Some PIN FRs, notably phosphine oxide, red phosphorus and phosphonates to a lower extent, can also interfere in the flame by releasing PO radicals and/or by other mechanisms, that are not necessarily well understood. Unlike halogens, PIN FR will not release corrosive gases, but as all FR disturbing the combustion process within the flame, they will impede a complete combustion, which typically results in smoke production.

2) chemical action in the condensed phase
a) Char formation: most phosphorus FRs, typically phosphates and polyphosphates, which release non volatile polyphosphoric acid that will in turn remove chemically-bound water from the polymer and create a carbonaceous layer via complex esterification, cyclization and crosslinking reactions. Nitrogen FRs can be useful to participate in the crosslinking reactions, thus enhancing the stability of the char. The thus created carbon-rich layer will act as a physical barrier to oxygen.

b) Formation of a glassy / ceramic-like layer can be obtained by using boron compounds, such as zinc borate, melamine borate, low-melting glasses and few others. The formed glassy layer can act as a physical barrier on its own, or be used together with char-forming additives to improve the char formation or reduce smoke formation.

3) chemical action in the melt phase
This is particular mechanism that only applies to specific FRs in given polymers. Typically examples are melamine cyanurate in polyamides or amino-HALS structures in polyolefins. Upon decomposition of these FRs, the breakdown products will be released that will lead to a non-burning polymer decomposition. This mechanism basically removes fuel from the heat source and can be very helpful in certain fire tests.

4) physical action in the gas phase
Metal hydrates (ATH, MDH) are the main examples. Upon endothermic decomposition, they release water vapour, which absorb energy, release water vapour and reduce smoke formation.

5) physical action in the condensed phase
Intumescence is a particular mechanism based on the formation of a char foamed layer that thermally insulates the underlying substrate. This can be both used to protect plastics (preventing further decomposition and contribution to the developing fire) or non-flammable materials, such as metallic structures. When used in thermoplastics, intumescence effectively offers a “build-in” anti-dripping mechanism.

FLAME RETARDANTS IN THE DISCUSSION

FRs have become a hot discussion topic since a couple of decades, raising questions about toxicity and their environmental footprint.

While it is recognized by the industry that not all products are perfect, the member of pinfa share the common vision of continuously improving the environmental and health profile of their flame retardant products. Therefore, pinfa members seek to dialogue with the users of PIN FRs in order to
identify their needs and technologies they are looking for.

pinfia also co-operates with national & supranational organisations (EU, OECD, United Nations) & other industry associations, consumer organisations & non-governmental organisations and will ensure the development of scientific knowledge related to the whole life cycle of PIN FRs, as demonstrated by the involvement within the EU funded ENFIRO project or the US EPA alternatives assessment programmes.
The Development of a Standard Test for Assessing the Effectiveness of Transit Vehicle Fire Extinguishing Systems

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INTRODUCTION
Rationale for this work
Whilst fires in transit vehicles are a small fraction of overall fire occurrence (car fires represent the vast majority of vehicle fires) they still occur frequently. Data from NFPA estimates the annual number of bus fires as 2,350 per year or about 6.4 fires per day.
In comparison with many other branches of fire protection, few standard approval tests exist for fire extinguishing systems for commercial vehicles, such as transit vehicles, coaches etc. As far as the authors are aware, the only approval test specifically for transit vehicles is SBF 128. Currently SP Technical Research Institute of Sweden (SP) is in the process of defining a more robust approval test. Despite this lack of approvals, many fire protection systems have been installed, but the precise pass/fail criterion was either not ascertained or has been lost in the mists of time. To address this issue, a test article has been constructed to evaluate the fire extinguishing performance of current in-house fire protection systems installed on commercial vehicles. This data will then be used as a benchmark against which the performance of future fire extinguishing systems can be judged.

EXPERIMENTAL
The test article
The test article (see Figure 1) was based on the dimensions of a representative US transit bus engine compartment. The dimensions are as follows: 2.50 m width x 1.35 m length x 1.18 m height. The height extension, shown on the left of Figure 1 is 1.22 m high x 0.41 m wide x 0.76 m long. To provide a robust and long-serving test article, the structure of the test article was fabricated using mild steel I-Beams, angle and sheet. Inspection windows were included to enable the fire tests to be captured on video. The top frame was made to be removable in order to a) enable the engine to be fitted easily and b) be replaced by a different configuration of engine compartment if and when required in the future.
As tested the article has a fully open base. It is believed that this is typical of city transit buses. Provision was also made within the design of the test article to fit plates to the base in order to create an enclosed or partially enclosed engine bay – an arrangement typically found in passenger coaches to reduce road noise and vibration. It was considered that the open base would represent worst case in terms of ease of extinguishment, as the agent would be more likely to be lost through the open floor.

Figure 1: Test Article
In order to have a realistic amount of clutter in the engine compartment it was decided to use a real engine within the test article. An IVECO 8060.45R six-litre diesel engine, complete with its ancillaries, (radiator, starter motor etc.) and transmission was installed in the test article. A fan capable of generating an airflow of 1.95 m³/s through the engine compartment was added, and used in three settings “off”, half or full-speed, the latter being equivalent to an engine speed of 2200 r.p.m.

**Fire threats used**

Three basic fire scenarios have been developed during the course of this work. All were based on fires involving diesel fuel, as fuel or flammable liquid fires are the most common. The first scenario comprised six relatively small, obscured fires in defined positions within the clutter and represented a fire in the early stages of growth. The second represented a more involved fire threat and comprised three large fires in the bilge area. The third fire threat was an intermittent fuel spray impinging on a preheated turbocharger.

**Small Fire Threat (~750 kW)**

![Figure 2: Layout of the Standard Fire Threat](image)

**Large Fire Threat (~1.6 MW)**

![Figure 3: Layout of the Large Fire threat](image)

**Turbocharger as ignition source and restrike threat**

A salvaged turbocharger was heated with a propane gas burner to approx. 600 °C and then sprayed with diesel fuel. This resulted in a reliable ignition source and a robust resultant Diesel fuel spray fire as long as the temperature of the turbocharger remained above 550 °C.
The photographs and charts below show the ignition sequence and that re-ignition occurs as long as the temperature is above 550 °C.

\[\text{Figure 4: Layout and graphical data from the Turbocharger threat}\]

**AGENTS TESTED**
The majority of this work has been carried out using dry chemical as the extinguishing agent. Agents tested included sodium bicarbonate, potassium bicarbonate from two different suppliers, and a potassium bicarbonate / urea complex (Trade name: Monnex™). More recently, some limited work has been carried out with gaseous agents 1,1,1,2,3,3,3-heptafluoropropane (HFC-227ea) Trade name FM-200 and 1,1,1,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone (FK-5-1.12), Tradename Novec 1230. Aqueous Agents: some exploratory work has been carried out using aqueous agents in a high pressure single fluid nozzle. Agents tested were Aquagreen XT (a low temperature foam) aqueous potassium bicarbonate and water as a baseline. More work in this area is planned.

**SUPPRESSION HARDWARE TESTED**
Three basic variations of system hardware tested are described in this paper.

**System 1**
This was a modified version of the “Standard” US Kidde transit vehicle fire suppression system. It was modified to allow different sized cylinders to be used, and the usual discharge valve was replaced by a ball valve to allow ease of operation. The system then comprised a single flexible hose to a 5 way manifold which in turn was connected to 4 nozzles, placed in the 4 upper corners of the engine compartment. This system is referred to as having a medium mass flow rate.

**System 2**
This was a simpler system where the manifold, four hoses and nozzles were replaced by a single hose and two larger nozzles in a 90° “Y” adapter, mounted centrally on the front wall of the engine compartment. An important feature of this system was that a larger outlet area was used resulting in higher mass flow rates. This, coupled with a normal cylinder pressure of 60 bar, ensured that whatever agent was being tested, it was discharged in a very short time of less than 2 seconds. Tests carried out with this system are referred to within the results section as high mass flow rate.

**System 3**
This was a high pressure single fluid water mist system comprising a cylinder, ball valve, 12 mm stainless steel pipework and two “cluster” style water mist nozzles. This type of system is referred to within the results section as low mass flow rate.
RESULTS & DISCUSSION

Table 1: Overall summary of Agents’ Performance, by Class

<table>
<thead>
<tr>
<th>Agent Type</th>
<th>Mass Flow Rate</th>
<th>Fire Threat</th>
<th>Presence of Airflow?</th>
<th>Hot Surface Re-ignition?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Chemical</td>
<td>Medium</td>
<td>Small</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large</td>
<td>OK</td>
<td>Challenged</td>
</tr>
<tr>
<td>Dry Chemical</td>
<td>High</td>
<td>Small</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large</td>
<td>OK</td>
<td>Challenged</td>
</tr>
<tr>
<td>Gaseous Agents</td>
<td>High</td>
<td>Small</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Aqueous Agents</td>
<td>Low</td>
<td>Challenged</td>
<td>OK</td>
<td>Fail</td>
</tr>
</tbody>
</table>

Some general trends are listed below:
In terms of dry chemical agents, Monnex was clearly the best agent, requiring the least mass to effect suppression. Potassium bicarbonate was more effective in some tests than sodium bicarbonate, and in other tests the two agents exhibited similar performance. All dry chemical agents performed better with a higher mass flow rate. The large fire threat was more challenging than small fires, and dry chemical provided some re-ignition protection.
Comparing gaseous agents, FM200 and Novec 1230 exhibited the same performance in terms of mass required to extinguish the fires. Both agents exhibited poor re-ignition protection.
The results for aqueous agents showed that AquagreenXT was superior to Aqueous KHCO₃ which in turn was superior to pure water. As would be expected, small fires proved more challenging than larger fires (less heat means that less steam is created). AquagreenXT was the only aqueous agent that provided re-ignition protection.

CONCLUSIONS
Within this cluttered test article and in the presence of airflow, merely increasing the quantity of suppression agent is not guaranteed to change a failed suppression result into a pass. This needs to be combined with either good distribution and / or an increase in agent mass flow rate.
The use of a more efficient extinguishing dry chemical agent, such as Monnex, can give more reliable extinguishing performance, when compared to other dry chemical agents such as sodium or potassium bicarbonate. However, there are other considerations such as thermal stability, corrosion, cost etc. that also need to be considered when selecting a suitable agent.
The tests with aqueous agents in the presence of airflow were disappointing, but not unexpected, given the relatively low flow rates used. However, if the airflow can be shut down prior to discharging the system, then aqueous agents may be considered for this application although fire location and size have been shown to challenge this type of system.
Using the diesel fuel spray and a pan fire as the ignition source gives information regarding the extinguishment or otherwise of the representative fire loads including potential fuel sprays, but does not give any information regarding the risk of restrike. Switching to a hot surface (turbocharger) as the ignition and restrike source gives a much fuller picture of the overall level of fire protection offered by the system under test.
Effectiveness of Shielding Vehicle Hot Surfaces

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ABSTRACT.

The purpose of this paper is a discussion of post-collision vehicle fires that are the result of engine compartment fluids (ECF’s) being expelled onto the hot surfaces of the engine compartment. The discussion will also address the effectiveness of shielding/guarding of the hot surfaces of the engine compartment.

The occurrence of post-collision engine compartment fires caused by the expelling of ECF’s in crashes has been researched, investigated and tested for many years. One of the areas lacking significant safety research is the testing of the ECF’s on actual vehicles both shielded and un-shielded that may be potential surfaces for auto ignition of the ECF’s.

Research in the past has been conducted using laboratory tests on a heated cylindrical/tube or an apparatus such as that used in ASTM E 659 to determine the auto ignition of ECF’s. Although prior testing has been listed a representing a plausible real-world scenario in which a combustible liquid may come in contact with a hot engine surface, no actual engine surfaces were used in the testing.

The testing conducted for this paper was on actual vehicles or vehicle components at operating temperatures. The results of this testing of ECF’s spilled, dripped and sprayed onto the vehicle exhaust systems and the effectiveness of production and prototype heat shields in reducing or eliminating post collision impact engine compartment fires will be listed.

This paper will discuss the effectiveness of production and prototype shielding to reduce or eliminate the risk of non-collision and post-collision engine compartment fires.
Protecting Automotive Cooling Fan Modules from Damage Caused by Thermal Runaway

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ABSTRACT

In the harsh automotive environment, power Field Effect Transistors (power FETs) are routinely subjected to extreme temperature variations and thermo-mechanical stress. Intermittent shorts, cold operating environments or noisy short circuits, as well as inductive loads and multiple short circuits can, over time, fatigue the device and cause it to fail in open, short or resistive mode.

Although power FETs are increasingly robust, they are prone to failures which can occur very quickly if their ratings are exceeded. If the maximum operating voltage of a power FET is exceeded, it goes into avalanche breakdown. If the energy contained in the transient overvoltage is above the rated avalanche energy level, the device will fail; causing a destructive thermal event that may result in smoking, flame or desoldering.

The resistive mode failure is of particular concern, not only for the power FET but for the printed circuit board, or PCB. As little as 10W may generate a localized hot spot of more than 180°C, well above the typical PCB’s glass transition temperature of 135°C, which can lead to damage of the board’s epoxy structure and, possibly, a thermal event.

Improving power component performance by using design techniques that spread heat more evenly and by incorporating new heat sink materials, are some of the solutions that have been proposed to enhance thermal management in power electronics. Nevertheless, many designers currently rely on secondary protection to help stop thermal runaway events that can be generated by power component failures or corrosion-induced heating.

The most common approach is to use a thermal fuse/thermal cut-off (TCO) or a thermal switch. Both of these devices offer the designer wide and specific temperature activation characteristics in both AC and DC applications; however, they also can present challenges in the board assembly process. Because more and more printed circuit boards (PCBs) utilize only surface-mount components, using a through-hole device can translate to special mounting procedures and additional cost and complexity. Additionally, standard devices may not provide the ruggedness and reliability needed for automotive applications; whereas components that are qualified for the automotive environment are fully tested to meet stringent shock and vibration specifications and provide the proper DC ratings.

KEYWORDS: cooling fan modules, power component failure, thermal runaway, thermal protection

SECONDARY THERMAL PROTECTION FOR HARSH ENVIRONMENTS

In response to the need for a robust, reliable surface mount device that can help prevent thermal damage resulting from failed power electronics, TE Circuit Protection has introduced the Reflowable Thermal Protection (RTP) device. The secondary thermal protection device can be used to replace redundant power FETs, relays and heavy heat sinks typically used in automotive and industrial electronic designs.
Figure 1 illustrates a scenario where a failed power FET may not generate a hard short overcurrent condition, but rather a resistive short, which can produce unsafe temperatures through $I^2R$ heating. In this case, the resulting current may not be high enough to blow a standard fuse and stop thermal runaway on the PCB.

![Figure 1](image1.png)

**Figure 1**  
Power FET failure in resistive mode can lead to unsafe overtemperature conditions.

If a power component failure or a board defect generates unsafe overtemperature conditions the RTP device, which opens at 200°C (a value above normal operating temperatures but below lead (Pb)-free solder reflow temperatures), will interrupt the current and help prevent a potentially harmful thermal runaway condition.

As shown in Figure 2, the RTP device can be placed in series on the power line in close proximity to the FET where it tracks the FET’s temperature and opens the circuit before a slow thermal runaway condition can generate an undesirable thermal condition on the board.

![Figure 2](image2.png)

**Figure 2**  
In a slow thermal runaway condition, the RTP200 device tracks the power FET temperature until it opens the circuit at 200°C.

**PROTECTING COOLING FAN MODULES**

Cooling fan modules (CFMs) are an essential element of the vehicle’s HVAC and engine cooling systems, helping to cool the engine and prevent potential overheating under specific conditions, such as hot weather and steep-hill driving. Figure 3 shows placement of the RTP device in a CFM...
application. CFM modules are typically placed under the hood and they experience more extreme temperature variations than those found in the passenger compartment. This thermal stress can accelerate fatigue of the power FET and lead to early failure. Under-the-hood components may also be exposed to "fluid attacks" leading to corrosion and localized hot spots on the PCB.

Typically, CFMs do not include a micro-controller which, under certain conditions, could be used for onboard diagnostics and automatic initiation of the turn-off signal to the power FET. As a result, a software approach to preventing power FET failure is not available, and secondary protection is needed so that thermal runaway does not cause a dangerous thermal event.

In most automotive cooling fan applications, power FETs are used in the control modules to switch power to the fan motor on and off as needed. There are two typical motor configurations used in CFM applications: brush and brushless. Figures 4 and 5 illustrate the two configurations and the associated electronics, and define the sensitive area where power component failures could generate unsafe thermal runaway conditions. In these applications the RTP device is placed in the sensitive area of the application and will open the circuit as soon as it sees a temperature above its opening temperature.
**Figure 5**  *Brush DC motor configuration.*

**HOW IT WORKS**

To allow it to open at 200°C in the field, the RTP device utilizes a one-time electronic arming procedure to become thermally sensitive. Before arming, it can withstand three Pb-free solder reflow steps without opening. Timing of electronic arming is user-determined, and can be implemented to occur automatically at system power up or during system testing.

The RTP device’s 200°C open temperature helps prevent false activations and improves system reliability since it is a value above the normal operating window of most normally functioning electronics, but below the melting point of typical Pb-free solders. As a result, the device will not open if surrounding components are operating in their target temperature range, but it will open before a component de-solders and creates the potential risk of additional short circuits.

**SUMMARY**

The RTP device can help meet the reliability requirements of automotive power electronics systems such as cooling fan applications, as well as ABS, power steering, PTC heaters, etc. The surface-mount device can be quickly and easily installed using industry-standard pick-and-place and Pb-free reflow equipment, and can withstand multiple reflow passes with peak temperatures exceeding well over 200°C and yet, in the field, will open if it detects a temperature above 200°C.

The device’s thermal sensitivity is beneficial since, in some cases, failed power components may not generate a dead short circuit overcurrent condition, but instead may create a resistive short that cannot be opened by a traditional fuse. This type of event may actually reduce load current, but can still result in unsafe thermal runaway conditions. The RTP device helps prevent damage caused by both dead short circuit and resistive short circuit conditions.
Fires in Rolling Stock – Testing and Validation
FIVE 2012

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CASE STUDY
Hundreds of passengers’ frequent stations throughout the Essen area every day and therefore the importance of protecting them against the risk of fire are clearly evident. Fire protection requirements with respect to train stations, particularly underground stations, are exceptionally demanding and the cost of implementing traditional solutions is costly.

The following case study examines the use of active fire protection systems, as well as testing and validation for the refurbishment of railway vehicles on the Essener Verkehrs AG (EVAG), who is a rail vehicle operator in Germany, as an overall strategy for lowering fire risk and examines a cost effective solution in protecting passengers.

Essen is a city in the central part of the Ruhr area in North Rhine-Westphalia, Germany. It is located on the River Ruhr and has a population of over ½ million people. Essen is linked to the surrounding towns and cities by a comprehensive railway network. Essen and these surrounding cities are served by a large number of railway stations many of which are very old and do not comply with current safety requirements mandated by the latest fire protection standards.

Refurbishment of these stations to meet modern fire protection standards would therefore be very costly and in some cases almost impossible to achieve. Current thinking in Essen has therefore been to find an economic solution which can be used as an alternative to traditional fire protection solutions and was expanded to embrace the protection of the trains themselves as they actually pose a considerable fire risk at stations.

A basic requirement of any fire detection and fire suppression system is effective fire control, by limiting the spread of combustion, in the shortest possible timeframe during the fire formation phase. One primary objective is to control the fire in the shortest possible timeframe so that passengers can be evacuated.

A positive outcome in using active fire protection systems on board of rail vehicles was recognition of a ‘compensation arrangement’ which realised the benefit of protecting the vehicles as part of an overall fire protection strategy. The ‘compensation arrangement’ not only recognised the additional protection afforded to rail vehicles it importantly recognised associated benefits in relation to the reconstruction works associated with underground stations such as those in Essen.

This meant that the assessment of fire risk for trains and underground stations was considered lower. This influenced the fire protection measures applied for the underground station areas and recognised the enhanced protection given to passengers.

In the following the basis for fire risk analysis, fire tests and the validation process of active fire fighting systems for rail vehicles will be shown.

EVALUATION OF FIRE RISKS WITH HELP OF FIRE RISK ANALYSIS
Combustion is an exothermic process between a fuel source and oxygen that produces heat and light. The requirements for a fire comprise four parameters: combustibles, an oxidation medium, energy and
the correct ratio between the combustible and oxidation medium. This is typically illustrated in what is called the ‘Fire Triangle’ (Figure 1).

Figure 1: Fire Triangle

If any one of these parts is taken away no fire can start, spread or exist. This Fire Triangle is the basis for a fire risk analysis.

A fire risk analysis again is the basis for a fire protection concept for rail vehicles. For the risks that are evaluated in the fire risk analysis, measures how to avoid fires, fire spread etc. must be found. Also the evidences of how fire protection measures are realized must be shown. One example of how to realize fire protection measures can be using active fire protection systems.

FIRE TESTING AND VALIDATION – SHOWN ON AN EXAMPLE (EVAG)

Active fire protection systems have the positive effect of taking away two parts, the oxidation medium (inertisation effect) and the energy (cooling effect).

The EVAG solution uses high-pressure water mist technology for fire protection in rail vehicles. This technology uses nebulisation by high-pressure and special nozzles of the reaction surface of water substantially enlarging its surface area compared to conventional systems. The distinctive cooling effect of water not only suppresses the fire but also protects people and goods from any negative influence of heat. The so called housing-in effect (filling the room with water mist and housing-in the fire) is very positive in this area. The small water droplets evaporate very fast so that energy and oxygen is abstracted out from the fire, called the ‘inertisation’ effect. Inertisation only takes place where a high level of temperature exists. Hence the combustion process is effectively fought at the surface of the fire and fire spread is detained.

For validating the active fire protection system IFAB conducted fire testing with and without activation of the system.

Figures 2 and 3 show the difference of the toxic gas concentrations by not using or by using active fire protection systems. It can be seen that the toxic gases are lowered significantly by activation of the system. Also it can be seen that the oxygen concentration by using active fire protection still can guarantee a survivable atmosphere for passengers.
Furthermore the burning behaviour of materials and temperatures were measured. To get realistic values not only single parts of the used material was burned. IFAB built up a 1:1 full scale fire scenario whereby original parts of the vehicles were built up. Figure 4 shows the parts that were used for the fire tests.

Figure 4: 1:1 Full Scale Test – Built up part

Figure 5 shows the fire scenario without using active fire protection. The fire scenario was based on a traveling bag which was ignited by a newspaper (different places inside the vehicle were tested). In this case the fire spread via the window rubber to the ceiling. After 6 minutes the flash over arose.

Figure 5: 1:1 Full Scale Test – Fire scenario without active fire protection

Figure 6 shows exactly the same scenario but by using active fire protection. In this case the ignition source was suppressed actively and only small parts on the seat were burned. Fire spread and flash over was avoided. A survivable atmosphere for passengers was built.

Figure 6: 1:1 Full Scale Test – Fire scenario using active fire protection
RESUME / FUTURE OPPORTUNITIES

A positive outcome in using the fire suppression technology on board rail vehicles was the affirmation of a ‘compensation arrangement’ which recognised the benefit of protecting rail vehicles as part of an overall fire protection strategy. The ‘compensation arrangement’ not only recognised the additional protection afforded on rail vehicles, it importantly recognised that enhanced levels of fire protection could be achieved for reconstruction works associated with the underground stations, such as those in Essen.

The ‘compensation arrangement’ became an effective tool to reduce the fire protection requirements at stations and buildings.

In recent times, public expectation with respect to safety has risen significantly; this is reflected in many areas of law, including OHS and rail safety.

The final solution was a cost effective outcome for the protection of trains and underground stations in the greater Essen area.

Active fire protection systems have historically been based on prescriptive technical specifications and directives mandated by public authorities. However, the work done at Essen illustrates that rising standards for fire resistant materials and the integration of fire resistant walls and doors into vehicle safety has imposed restrictions on the freedom of design and is in direct conflict with the desire to build vehicles of aesthetically ambitious design which allow economical and operational efficiency.

In addition, crumbling prices occurring during negotiations for the building of new rail vehicles is often an issue pushing the development of new vehicle concepts to the verge of failure. The demand for new onboard technically heavy weight solutions can also lead to axle load problems for regional train sets.

Specifications requiring the integration of heavy-weight fire-protection doors, will confront engineers with nearly insoluble problems. For this reason, vehicle manufacturers are moving away from mandating ‘word for word’ compliance and increasingly looking for alternative technical solutions while demonstrating the underlying requirement of ‘proof of equal safety’. The use of active fire protection systems using high-pressure water mist technology offers an alternative approach in protecting passengers. This technology has been effectively used in protecting a large number of vehicles as compensation against the requirement of using fire protection doors and high level fire protection material specifications.

Fire tests on 1:1 scale vehicles have demonstrated equal levels of safety can be realised compared to traditional systems of fire protection and have now been accepted by public authorities and experts involved in the area of fire protection in Europe. An analysis of test data confirms that the system not only rendered proof of equal safety, but also shows that a substantially higher level of safety is achieved by comparison to traditional systems, such as the use of fire protection doors. The benefit of high-pressure water mist technology is that it directly impacts on the burning process, i.e. on the initial fire and creates a safe low-temperature environment around the fire source. The benefit associated with a reduction in the thermal effects of the fire on the vehicle body structure is also significant.

The use of active fire protection systems has also shown positive outcomes on aspects such as the operability of rolling stock. Based on these types of benefit, manufacturers such as ThyssenKrupp Transrapid embraced the use of active systems for their project in Munich.

In official correspondence, experts have presented vehicle manufacturers several options for mitigating the risk of fire risk by compensation using alternative fire protection technologies. When incorporating active systems for fire protection, several advantages have been realised, such as the omitting of fire protection doors, using lower standards of material for the ceiling area, using materials with lower requirements in the sitting area, omitting the arithmetical proof of operability during the critical fire phase, the simplification of evacuation concepts, as well as smaller dimensioning of smoke exhaust systems at railway stations.
The Key to Suppression is Detection

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OVERVIEW

The vast majority of fire events in buses begin as small fires. When detected quickly, a fire’s impact can be minimal, with damage often limited to the failed component. Delays in the detection of the fire allow it to grow rapidly due to the available fuels for the fire: oil, hydraulic fluid, diesel, and of course, the structure of the bus which is frequently fiberglass. Selection of a detection methodology that will reliably detect a fire quickly, and will be free from false discharges, is a key component to suppressing a fire.

BUS FIRE STATISTICS

Bus fires are far more prevalent than municipalities and motorcoach companies are willing to admit. Statistics show that bus fire incidents are increasing, even with the newer fuel technologies, like Compressed Natural Gas (CNG) or Gasoline-Electric Hybrid coming to the market place. Also, bus manufacturers have been forced to change bus designs due to low emissions legislations and the need to become more environmentally responsible. These changes are actually forcing buses to operate at a higher internal temperature than ever before.

Organizations like the National Fire Protection Association (NFPA) and the Federal Motor Carrier Safety Administration (FMCSA) have studies and evidence pointing to the need for reliable fire suppression solutions. The study conducted by the NFPA in 2006 indicated that 2,210 bus or school bus fires occur each year, amounting to roughly six fires each day. The resulting cost of three deaths and 30 injuries nearly 24.2 million dollars in property damage. The FMCSA study conducted by The Volpe National Transportation System Center concluded that there were a reported 899 motorcoach vehicle fires reported from 1995-2008, roughly 70 per year. The FMCSA numbers are rough estimates and considering that there is no central depository for fire data or safety data of any kind, it is difficult to know the true number of incidents. Insurers like Lancer indicate that in the event of a fire the loss is on average $100,000. Considering the frequency of fire, the cost of including a fire suppression solution in each vehicle will far outweigh the potential loss of dollars, personal injury, and reputation of the fleet. Table 1 illustrates this by breaking the damage down into specific locations and determining the cost of damages (in U.S. dollars).
FIRE SAFETY RECOMMENDATIONS

These statistics and the experience of municipalities have led to the inclusion of fire suppression on some fleets. The American Public Transportation Association (APTA) developed recommended practices for inclusion of fire safety, but these are merely a recommendation therefore open to interpretation and implementation based on each fleet. Taking recommendations for fire safety to the next level, the FMCSA developed legislation to require the inclusion of vehicle fire suppression on motorcoach vehicles nationwide. Further research is to be conducted on fire suppression solutions and appropriate protection for these vehicles. This legislation was reintroduced in 2011.

Vehicle fire suppression is not new, tried and tested technologies are available in the market place for all vehicle sizes. The challenge for end users and buyers in the industry are to understand the pros/cons of the solutions and potential pitfalls for detection and activation of the agent. Agent selection is one important factor to consider but more importantly the detection and activation of the agent in the event of a fire. Even with the right agent and nozzle placement, if the detection methods do not catch the fire—or there is a delay in detection—the fire will be allowed to grow increasing the damage to the bus as well as the fire suppression resources necessary to combat it.

CAUSES OF BUS FIRES

A common thread among reported fire incidents points to engine and electrical malfunction. According to the NFPA study 59 percent of fire incidents were the result of mechanical failure or malfunction and 25 percent a result of electrical failure. According to the Volpe report, the engine compartment is the leading location of fire incidents followed by wheel wells.

The risks in the engine compartments include fuel line ruptures, other flammable liquids, debris and grease build up on the engine block, frayed or electrical wiring as well as heat from the turbocharger and exhaust are all ignition points for fires. Table 2 illustrates this in motorcoaches by showing both the specified and unspecified ignition points.

Table 1  Average Estimated Damage per Vehicle from 1995 to 2006, by Fire Location

![Table 1: Average Estimated Damage per Vehicle from 1995 to 2006, by Fire Location](image)

*Motorcoach Fire Safety Analysis, FMCSA, p. 37*
Table 2  Motorcoach Fire records with and without Specified Ignition points, 1995-2008

Allowing a fire to spread from the engine compartment and source of the fire creates a significant safety risk. The Volpe study says a fire in a motorcoach vehicle can fully engulf the vehicle in just 15 to 20 minutes. This leaves very little time between ignition and total loss of the vehicle forcing the passengers and operator to quickly exit a burning vehicle, increasing potential injury and weakening public opinion.

**STEPS TO PROTECTING PASSENGERS**

Fire suppression systems of every shape and size are available in the market place, but the key to successful suppression lies in the detection method. There are many challenges to effective detection and suppression of a fire in an engine compartment including:

- Airflow
- Debris build-up
- Temperature variations
- Shock and vibration
- Humidity
- Salt

Dust, debris, temperature extremes, routine cleanings and most importantly the airflow in a moving vehicle all play a role in the ability of a fire suppression system to effectively detect a fire. An efficient fire suppression solution needs to resolve all of the above issues and provide the best possible detection and suppression for any vehicle application.

**DETECTION AND AGENT**

Options for detection include thermal/infrared detectors, heat detection wire, and linear detection tubing. Depending on the application, the most appropriate solution should be considered. An effective detection method will detect and suppress a fire in about twenty seconds. This is the optimal time frame that will limit damage to the failed bus component, before it spreads to and damages other areas of the bus.

Activation alternatives include automatic, electrical and manual activation. Activation can be combined with multiple methods allowing for immediate suppression, delayed activation and/or operator decision to discharge the agent.

\[\text{Motorcoach Fire Safety Analysis, FMCSA, p. 38}\]
The type of agent can range from water mist to clean agent (e.g. Novec 1230) to dry chemical (e.g. ABC Dry Chemical), depending on the exact form of vehicle application. Most commonly a dry chemical is recommended when used in the bus engine and electrical compartments. Dry chemical is best able to extinguish fires even in well-ventilated compartments. Also the dry chemical agent does not short out electrical systems where liquid based agents may cause a concern.

RELIABILITY

Reliability is perhaps the most important factor when assessing the value of fire suppression systems. Given what the internal environment of a bus is exposed to (day in and day out): the dirt and contaminants build-up in engine compartments, plus shock and vibration, humidity, road debris, and the extreme temperature variations throughout the year tend to favor simpler systems and thus demonstrating increased reliability, because they do not have complex parts to maintain and replace in that harsh environment. A fire suppression system that is easy and inexpensive to maintain and will not be damaged through the daily wear and tear of the vehicle is of the utmost importance and must be considered.

SUMMARY

The impact and prevalence of large bus and motorcoach fires could be reduced significantly by the selection of fire suppression systems that react quickly to fire. When organizations are considering fire suppression systems it is very important to consider the detection method as the most important element of the system and then the agent as well as the reliability of the overall system. Detection and suppression work hand in hand; if the fire is not effectively detected, the fire will never be suppressed.

KEYWORDS: detection methods, fire statistics, causes of fires

REFERENCES


Fire Safety Improvement of Vehicles

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ABSTRACT

A great number of vehicle fires start in the engine compartment. The combination of fuel, electrical current and large or numerous plastic parts makes the under-the-hood vehicle area prone to fire. Improving fire safety of plastics under-the-hood could potentially have a significant benefit to life, property and potential environmental pollutants that result from fires. To facilitate passenger survivability, preventing or delaying the penetration of flame into the passenger compartment is extremely important. While wire and cable insulation and battery cases and trays are commonly flame retarded, much of the plastic used in under-the-hood applications of vehicles do not contain flame retardants to improve fire safety. For example, vehicle electrical connectors, plastic engine shields and plastic manifolds are a few of the plastic parts that are not generally flame retardant. In addition to existing concerns, new technologies (electric, hybrid and alternative fuel vehicles), which are an essential part of our sustainable future, present additional fire safety risks that need to be understood.

Vehicle recalls and accidents help to identify specific fire safety areas of concern. This paper will address some of these areas and suggest possible improvements. The results of fire tests that summarize some improvements will be presented.

INTRODUCTION

In the 1950’s, there was practically no plastic found in vehicles [1]. The use of plastics in vehicles increased to ~22 lb per vehicle in 1960 and ~245.5 lb in 2000 [2, 3]. In 2007, there were ~330 pounds per vehicle of plastic on board [4]. Today, a typical vehicle is made of >50% by volume plastics and polymer composites; however, these materials only account for ~10% of the total weight of the vehicle [3]. Plastics improve fuel economy by reducing weight. This has improved automobile gas mileage and had an overall positive effect on the emissions reduction of greenhouse gases. Increasing fuel efficiency requirements should drive weight reduction and further increase plastic consumption.

Vehicles utilize plastics in a multitude of places. Plastics used in panels, trim, lighting, ducts, electronics, and foam and textiles that make up the upholstery and headliners, dominate the passenger compartment. In addition to exterior body panels, fuel storage and delivery systems, use of plastics in the engine compartment has been around for many years and is increasing. Housings, connectors, relays, wire and cable coating, supports, electrical parts and flexible and structural parts are all plastic parts used under the hood. Plastics make a significant contribution to the overall make-up of vehicles, with continuing growth expected.

Most plastics are flammable. The fuel load of the plastic components in an average automobile is roughly equivalent to a full tank of gasoline (3 x 10^9 J) [5]. For fire safety reasons, flame retardants have been used in some, but not all, vehicle applications for many years.

FIRE SAFETY IN VEHICLES

The Motor Vehicle Safety Standard (MVSS) No. 302 flammability test was adopted more than 35 years ago to prevent rapid flame spread from small ignition sources, such as cigarettes, in a vehicle passenger compartment [6]. At the time of adoption, plastics were used primarily in the passenger compartment. Since this time, increases in operating temperatures under the hood, proliferation of
electrical and electronic equipment in the passenger compartment, and driver comfort systems, have all become realities. Hybrid and Electric cars also are beginning to change the vehicle landscape.

While the MVSS 302 flammability test has certainly helped to reduce the number of vehicle fires, they continue to be a significant issue. From 2004-2006, about 258,500 highway vehicle (automobiles, vans, trucks) fires occurred each year [7]. Highway vehicle fires accounted for ~90% of the total vehicle fires and 16% of all fires. About one in six fires during this time was a highway vehicle fire. They resulted in about 490 deaths, 1,275 injuries, and $1 billion in property loss each year.

Highway vehicle fires also accounted for 14% of all fire deaths [7]. Of these highway vehicle fires, 62% originated in the engine area. For fatal highway vehicle fires, 34% originated in the engine area. The leading factor contributing to the ignition of highway vehicle fires (47%) was mechanical failure.

Studies have shown that most plastic parts exposed to fire melted, were easy to ignite, had rapid flame spread and burned as high heat release rate fires [8]. Also, many engine compartment fluids are easy to ignite. These studies indicate that during a fire a combination of engine compartment fluids and/or flammable plastic parts could produce flames that penetrate the passenger compartment. Tests performed on automotive components used in engine and passenger compartments showed that they were as flammable and ignitable as the commodity and engineering plastics of which they are made, and much more flammable than those used in the interiors of aircraft [8].

AREAS TO ADDRESS FIRE SAFETY IMPROVEMENTS

Since the engine compartment consists of a combination of some flammable fluids and plastic parts and it is well documented that a significant percentage of fires originate in the engine compartment, it seems that improving fire safety of plastics under the hood could potentially have a significant benefit. While wire and cable insulation and battery cases and trays are commonly flame retarded, much of the plastics used in under the hood applications may not contain flame retardants to improve fire safety. For example, automotive electrical connectors do not generally contain flame retardant.

Flame retardants are used in a variety of consumer products to reduce fire risk at various stages of the combustion process. They help prevent fires from starting, delay the spread of fires or delay the time of flashover to enable people time to escape. They play a significant role in making homes, hotels, hospitals, nursing homes, offices, automobiles (interiors) and other means of transportation safer. Vehicle parts used under the hood for electrical applications (connectors, switches, and relays) are typically not flame retardant, while these parts are generally flame retardant for applications other than automotive (electrical and electronic equipment, aircraft, etc…). This type of application needs to have high temperature stability to avoid mechanical failure in service and resist arcing. Glass-filled (30%) polyamide 6,6 (PA 6,6) is a common engineering thermoplastic used in connectors, switches and relays in other electrical equipment. The PA 6,6 used in the majority of these vehicle applications does not contain flame retardants to improve fire safety. This plastic also finds use under the hood as manifolds and in other component housings.

EVALUATIONS

Both flame retardant (FR) and non-flame retardant (non-FR) PA 6,6 formulations were prepared and evaluated in order to demonstrate the flammability properties of potential under the hood electrical parts [9]. Technology exists to easily flame retard PA 6,6. A polymeric brominated polystyrene FR, SAYTEX® HP-3010 Flame Retardant, was used to prepare and test FR formulations that are similar to formulations currently used commercially in other applications. Both FR and non-FR formulations contained 30% glass fibers. The tests performed on these formulations were the MVSS-302 flammability test and the UL-94 vertical burning test.
Figure 1 FR PA 6,6 after the MVSS-302 Test

Figure 1 is a picture of the FR PA 6,6 after the MVSS-302 flammability test was performed. The FR PA 6,6 demonstrated a high level of fire resistance in this small-scale test.

Figure 2 is a picture of non-FR PA 6,6 after the MVSS-302 flammability test was performed. Even though this material passed the MVSS-302 test, the sample burned completely. The only remaining portion of the sample was that protected by the specimen holder.

Figure 2 Non-FR PA 6,6 after the MVSS-302 Test

All formulations passed the MVSS-302 at both a 1/16” and 1/32” thickness, due to the material not igniting or having a burn rate below 4 in/min. Table I contains the results and burn rates from these tests. The FR PA 6,6 did not ignite and, as such, could not support combustion. The non-FR PA 6,6 ignited and supported combustion at rates of 0.8 - 2.5 in/min and continued to burn until the samples were consumed (except where the specimen holder protected the sample). Table I contains the results. The fact that the non-FR PA 6,6 ignited, supported combustion and continued to burn until the samples were consumed, demonstrates the need for improvements in this particular test.

Table I MVSS-302 Test Results

<table>
<thead>
<tr>
<th>Material &amp; Thickness</th>
<th>FR</th>
<th>Non-FR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA 6,6 1/16”</td>
<td>Did Not Ignite - PASS</td>
<td>1.0 in/min - PASS</td>
</tr>
<tr>
<td>1/32”</td>
<td>Did Not Ignite - PASS</td>
<td>1.6 in/min - PASS</td>
</tr>
</tbody>
</table>

Below are pictures from the UL-94 flammability tests on the FR and non-FR GF PA 6,6.

Figure 3 UL-94 test on GF PA 6,6 At the start of the test

Figure 4 UL-94 test on FR GF PA 6,6 After 2nd 10-sec flame applied

Figure 5 UL-94 test on non-FR GF PA 6,6 After 1st 10-sec flame applied
Table II  UL-94 Flammability Ratings

<table>
<thead>
<tr>
<th>Material &amp; Thickness</th>
<th>FR</th>
<th>Non-FR</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF PA 6,6 1/16&quot;</td>
<td>V-0</td>
<td>BURN</td>
</tr>
<tr>
<td>1/32&quot;</td>
<td>V-0</td>
<td>BURN</td>
</tr>
</tbody>
</table>

The results of the UL-94 flammability test on flame retarded and non-flame retarded PA 6,6 can be seen in Table II. They showed a significant difference in flammability. This difference could have a dramatic impact on whether or not electrical parts ignite, such as a malfunctioning part that short circuits and arcs. Figure 3 is a picture of the test specimen as the flame is applied during the UL-94 test. Figure 4 is a picture of the FR GF PA 6,6 after the second 10-sec application of the Bunsen burner flame. The sample did not ignite or support combustion and achieved the best rating in this test, a V-0. Figure 4 is a picture of the non-FR GF PA 6,6. Both thicknesses burned for more than 30 seconds after the first 10-sec application of the Bunsen burner flame and burned completely up to the specimen clamp. This resulted in failure to obtain passing ratings (V-0, V-1, V-2) and both received “BURN” ratings.

CONCLUSIONS

The combination of fuel, electrical current and a growing number of plastic parts makes the area under the hood vehicle more prone to fire than in the past. Small-scale flammability tests have been performed on materials that are typically used under the hood in connectors, switches and relays to determine if improvements in fire safety could protect against fires that could originate in this area. The flammability tests were common tests that are used to evaluate automotive, electrical and other materials. The results showed that slow burning materials, such as glass filled polyamide 6,6 that did not contain flame retardants, passed the MVSS-302 flammability test, despite burning completely when exposed to a small flame. The UL-94 vertical burn testing demonstrated the ability of the addition of polymeric brominated polystyrene FR, SAYTEX® HP-3010 Flame Retardant, to plastic parts to suppress flames and not support combustion. These results demonstrate that flame retardant plastic parts could be used to help prevent fires from starting in plastic applications under the hood and/or slow down the spread of fires that could penetrate the passenger compartment. This is particularly relevant when high temperature stability is needed to avoid mechanical failure in service and resist arcing.

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Energy storage system safety in electrified vehicles

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ABSTRACT
The environmental challenges with CO\textsubscript{2} emissions and a diminishing oil reserve drive the need of a broad introduction of electrified vehicles. The relatively new lithium-ion battery technology offers batteries with increased energy and power densities. Li-ion technology requires a monitoring system since its safety window is lower than many other battery technologies. In an energy storage system for electrified vehicles safety aspects thus have to be taken into serious consideration. In this paper fire as a consequence of malfunction or abuse of the energy storage system is discussed.

KEYWORDS: energy storage system, electrified vehicle, lithium-ion, battery, safety, thermal runaway, fire

INTRODUCTION
An electrified vehicle has a traction system which can be either pure electric or a combination of electric and some other source (e.g. fossil fuel). New battery technologies, e.g. lithium-ion, makes it possible to build electric vehicles (EV) and plug-in hybrid vehicles (PHEV) with acceptable driving range with zero emissions. The Li-ion cells offer high energy and power densities and are constructed with advanced materials. There are however, still aspects to consider for these new technologies and electrified vehicles. A drawback is that the window of stability is relatively small (both regarding temperature and voltage region) and the lithium-ion cell materials are volatile and flammable. Safety is thus an important issue due to the combination of the reactive nature of the cell materials and the presence of hazardous voltages in the vehicle.

LITHIUM-ION BASICS AND THERMAL EVENTS
Lithium-ion cell technologies have been used for more than 10 years in consumer products, such as laptop computers and mobile phones. During the years, there have been fire incidents with these batteries. The last 5 years, reports have been made regarding battery fire incidents in e.g. laptops, iPods, cargo planes and electric vehicles [1].

Lithium-ion cells consists of different layers, essentially; anode, separator, cathode and electrolyte. The electrolyte consists of organic solvents, lithium salt and additives. The electrolyte recipe is every cell manufacturer’s secret, especially regarding the additives. The organic solvents, e.g. ethylene carbonate (EC) and dimethyl carbonate (DMC) are flammable. Lithium is a reactive metal while the lithium-ion is more stable. Lithium metal can however be formed during normal and abusive use.

Under abuse or malfunction conditions, the lithium-ion cell temperature can increase. If the temperature reaches typically 120-150 °C, exothermic reactions within the cell starts. The exothermic reactions will further increase the temperature, which could start additional exothermal reactions. If the overall cell reaction creates a rapid temperature increase, it could result in a so called thermal runaway, which could consist of one of or a combination of the following; rapid gas release, electrolyte leakage, fire, rapid disassembling/explosion.

Figure 1 shows an overview of the potential chain of events for a thermal runaway. On the left side in the figure, the sources of a cell temperature increase are shown. Furthermore, one cell could affect the
adjacent cells. In a worst-case scenario the thermal events from one of several cells could spread and affect the complete energy storage system.

Figure 1. Potential chain of events for a thermal event on the cell level developing to system level.

LI-ION FOR AUTOMOTIVE USE
The conditions and requirements put on lithium-ion batteries in automotive applications are different from those in consumer electronics. Basically, Li-ion batteries for consumer products do not meet the needs of the automotive industry. The safety aspects, which are discussed in this paper, are just one on many aspects which must be considered in a different perspective.

In order to meet the demand of the automotive industry, new lithium-ion battery materials have been developed. Lithium iron phosphate (LFP) is a more stable cathode material than the mainly cobalt-based lithium oxides that are commonly used in consumer Li-ion batteries. Researchers has also developed other electrode materials, for example mixed cobalt with other materials (e.g. Ni, Mn, Al) in order to improve safety and other aspects (e.g. life time, energy and power densities) [2].

The cell design, both chemical and mechanical, affects safety. The cell manufacturer can influence the electrolyte composition and its additives [3], e.g. flame retardants, redox shuttles and gas release controller. The selection of the active electrode materials (anode and cathode) also affects the thermal runaway and its onset temperature. The mechanical packaging, e.g. cylindrical, soft or hard prismatic can or pouch prismatic, also affects the cell behavior during a thermal event. For example, a cylindrical cell could build up a much higher pressure than a pouch cell. There can be both positive and negative aspects on each cell packaging. For example, with a cylindrical cell it can be easier to control the venting direction. There are thus a number of safety mechanisms that can be included into a lithium-ion cell construction, by its manufacturer [4].

Lithium-ion batteries for automotive use have shown an increased safety regarding fire and explosion. Therefore, the focus of the lithium-ion safety have drawn more and more towards the safety aspects of released gases and smoke, as well as other electrical aspects, e.g. electromagnetic compatibility (EMC).

EXPERIMENTAL
In order to experimentally study thermal runaways in lithium-ion cells three cells of size 18650 were thermally abused in a thermostated oven. Two of the cells were standard laptop batteries from Samsung and Sanyo with unknown cathode composition, most likely cobalt mixed oxides. The third
The 18650 cell was manufactured by K2 Energy and had a lithium iron phosphate (LFP) cathode. The cell was fastened on a brick and centrally placed inside the oven. The oven was equipped with a fan system to circulate the air to achieve a uniform temperature. The cells were tested one at a time with continuous heating from ambient temperature up to the onset of thermal runaway or to max 300 °C, without any ramping or stops. Prior to the test, the cells were fully charged to 100% SOC according to each manufacturer’s charging instructions. Each cell was equipped with four thermocouples, placed uniformly with two sensors on the top and two sensors on the bottom of the cell. Figure 2 shows the average cell surface temperature for the three tested cell types.

All cells vented and got into thermal runaway. The cells from Samsung and Sanyo with the cobalt mixed oxide showed a very rapid temperature increase at the onset of thermal runaway. The LFP based cell from K2 Energy also entered thermal runaway but with a more modest temperature increase. Both Samsung and Sanyo cells started to burn during the thermal runaway while the K2 Energy cell did not burn. Table 1 shows basic cell data and extracted thermal runaway results where the rise time is the time between the onset and peak temperature of the runaway. The temperature rise is the difference between onset and peak temperatures of the runaway and the temperature rise rate is the ratio between temperature rise and rise time. As seen from the results the cell with the LFP cathode demonstrates a more safety performance than the laptop cells with a lower temperature rise rate and no fire.

Table 1. Basic data for tested cells and extracted results from the thermal runaway.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Cell data</th>
<th>Thermal runaway results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom voltage (V)</td>
<td>Nom capacity (Ah)</td>
</tr>
<tr>
<td>Samsung ICR18650-24F</td>
<td>3.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Sanyo UR18650F</td>
<td>3.7</td>
<td>2.2</td>
</tr>
<tr>
<td>K2 Energy LFP18650E</td>
<td>3.2</td>
<td>1.25</td>
</tr>
</tbody>
</table>
LITHIUM-ION BATTERY FIRE DEVELOPMENT

When discussing fire in an energy storage system, two main fire types should be considered. The first type is the reaction within the lithium-ion cell material itself, that is, reactions between electrolyte and electrodes. The special properties in this case are; an accelerated process due to exothermic reactions and self-supply of oxygen due to oxygen released by the reactions itself. Therefore, this fire is difficult to control and extinguish. In theory, the thermal runaway reactions could be stopped by cooling the cell below the onset temperature of the reaction. In practice, as seen in Figure 2, the temperature development is so rapid that simultaneous cooling is difficult to achieve after the onset of the thermal runaway, a more viable option is to make sure that the onset temperature is not reached.

The second type is a more traditional fire, that is, a fire which requires oxygen from its surroundings. It could be fires in e.g. plastics, cables and housing inside the energy storage system as well as in parts of the cell. Free electrolyte from cells or fire in plastic insulation and separator on a cell-level may be part of this type of fire. Furthermore, a fire of the first type, involving a thermal runaway inside a cell could start a fire of the second type, and vice versa.

The design of the energy storage system is important in order to make it possible to stop or retard additional cells from going into thermal runaway. As always with batteries, adding additional safety is a compromise that adds negative consequences, e.g. adds weight, volume and costs to the system. However, the access of fire fighting media to be applied on the cell surfaces inside an energy storage system is usually very limited due to the packaging design of energy storage systems and electrified vehicles. A lithium-ion cell which undergoes thermal runaway or other severe conditions (e.g. overtemperature) will react with swelling and could release gases, smoke and particles. The gases released during cell venting are flammable and could thereby be ignited by a spark in the vicinity. Regarding the electrified vehicle and the integration on the energy storage systems as well as the hazardous voltage systems in the vehicle, the design for crash safety is vital.

THE OVERALL SAFETY OF THE ENERGY STORAGE SYSTEM

The overall safety of a complete electric vehicle and energy storage system will not only be a function of the cell safety but also of many other parameters on the system level. The battery management system (BMS) is very important in order to e.g. monitor and prohibit critical situations, alerting the driver in case of a thermal event, activate potential available counter-actions and controlling the shut-down procedure of the system, which should be constructed under consideration of the complete safety of the electrified vehicle. The cooling system and the mechanical housing and structures are other important parameters. The positioning of the cells within the battery pack is also essential, and should e.g. consider cell venting properties.

In order to obtain a safe system, all components and its properties must be considered. One of the key design parameters to understand when designing an energy storage system for electrified vehicles are the mechanisms for spreading of gases, smoke, fire and heat from components (e.g. battery cells) to battery system and to the complete electrified vehicle.

ACKNOWLEDGEMENTS

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Total Fire Protection Solutions for road and railway vehicles.

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ABSTRACT
As the mandatory safety requirements protecting the passengers and staff in vehicles increases there is a risk that the cost and technical complexity increases if traditional methods of mitigating the hazards are used. The possibility of integrating subsystems can offer solution that has higher reliability, higher availability, higher safety integrity and lower life cycle cost. This paper gives an overview of technical possibilities using commercially available components and products creating system solutions fulfilling future requirements and standards. The paper refers to railway applications but the solutions are also applicable to other types of vehicles.

KEYWORDS: fire detection, fire safety, integration, controls, safety integrity

BACKGROUND
In Europe there is a lot of focus right now on the coming new fire safety standards for Railway applications. The EN 45545-1 to -7 with the title “Fire protection on railway vehicles” covers fire protection aspects from the requirements of the fire properties of materials, to the overall design of the vehicles. The goal is to achieve an optimal level of safety making it possible for the safe evacuation of passengers and staff in case of fire. The coming EN 50553 with the title “Requirements for running capability in case of fire on board rolling stock” supports in setting the requirements when operating trains in tunnels or on elevated structures.

The new set of standards will when released support the European Parliament and Council Directive on the interoperability of the rail system within the European Community as well as the safety in European Railway Tunnels described in each respective Technical Specification for Interoperability (TSI).

ADVANTAGES OF THE STANDARDS
The advantage of having these standards is of course that it simplifies the assessment of the fire safety level of all vehicles making it safer for the passengers and staff. It also simplifies the work for the industry as the design requirements for the vehicle and their component gets clear and will be the same in all countries within the community. In some cases however the development of standards may lead to heavier investments for the final customer. In the case of EN 45545 this is perhaps not the case as these new standards are built on other existing standards and regulations within UIC after having been adapted to the European market requirements. However if all system functionality specified in the standard together with other systems onboard are treated as separate systems in the work of engineering, installation, commissioning as well as all aspects from the vehicles operation during its lifetime, the cost can potentially be very high.

However the European Directive for Interoperability permitting the free movement of trains in the trans-European rail system together with the Tunnel Directive specifies that the implementation should be made in such a way that it delivers an optimal level of safety in the most cost-efficient way. In such cases a higher degree of integration can be very cost efficient and practical.

It should be noted that the Interoperability Directive and standards only specifies that it supports the safe evacuation of the passengers and staff and not the protection of the investments in vehicles, infrastructure and operation nor the environment. Even if the protection of passengers and staff comes
first, all train manufacturers and operators do what is practically possible to have a total protection of the full investment and environment.

The Common Safety Indicators mandatory for the operators to report and the authorities to follow up includes also the cost for stand still, cleaning up the environment etc. so these aspects are also important to cover when making the safety assessment prior to the design of the total system implementing the information as a part of the mandatory safety management system.

SAFETY INTEGRITY
In order to assure the best safety integrity it is of the highest importance to consider the definition of the safety function supporting the safe evacuation of passengers and staff. The safety function link should be as short as possible in order to reach a higher safety integrity level.

For example if a total fire safety solution for a vehicle is based on smoke detection in ventilation ducts, the ventilation or HVAC system automatically becomes a part of the Fire Safety System as the ventilation system then needs to be in operation at all times, otherwise you will not have a fully functional fire detection system. The same weakness in the system can be created if a fire detection signal of alarm gets routed trough other systems such as the train computer if the signal is intended to activate an automated suppression or extinguishing system. Of that reason it is important that a hazard analysis is made for the total system solution including all systems following the flow of signal and event from the first indication of fire such as smoke, heat or flame, to the final safety action that is expected from the system such as a power shut down, a suppression release or a closure of a fire door.

MODULARIZED SYSTEM SOLUTIONS MEETING INTEGRATION DEMANDS
In order to meet this future demand that is today literally on our doorstep Consilium developed and launched the new state of the art modularized Fire Detection System TS1000 (fig 1) meeting not only these new formal requirements but also the unexpressed need to make a higher degree of integration possible.

The basic functionality of the TS1000 system (figure 1) is of course to be a Fire Detection System. As the coming EN 45545 standards specify that the location of fire must be possible to identify and indicate the TS1000 system is mainly configured to be of the addressable type even though it can also operate as a conventional system. As the system also should have the right level of safety ensuring a reliable function during the time when it is required to fulfil its purpose even though it is exposed to fire, that is to support the safe evacuation of passengers and staff, the TS1000 can be easily configured for different levels of redundant functionality (Fig 2). The system is expected to support the evacuation in up to 15 minutes according to the standards. This requires not only a Fire Detection System supporting this in its basic design but also the correct engineering of the total train in terms of cable routing, power supply etc.
INTEGRATION AND CONTROL

The controls needed onboard a train referring to the EN 45545 varies depending on the technical solutions for e.g. ventilation/climate control, fire barriers, extinguishing and suppression, audible and visual local and remote alarms, public address, emergency lights, power control etc. All of the systems above can be a part of the total safety solution in order to reach the safe evacuation of passengers and staff and must of that reason be able to operate until they have fulfilled their purpose even if exposed to fire.

All of these controls can be delivered separately by different manufacturers but in order to reach the optimal level of safety in the most cost-efficient way the Fire Detection System should offer the control of all these functions integrated communicating the status to the Train Computer, the Event Recorder etc.

For the ventilation/climate control system the Fire Detection System already has all information for the controls. It is e.g. possible to control the ventilation by closing air inlets if smoke is detected in the air inlet ducts. In the same time it is possible to set the ventilation system in recirculation mode. All controls can be made local using the same communication wires adding no extra installation cost but the small remote I/O unit that is installed close to the ventilation unit.

For the extinguishing and suppression systems (Figure 2) it is often recommended and required the voting or “double knock” function. The voting or “double knock” function means that the extinguishing or suppression system does not release until two or more detectors are in alarm. This is to avoid unintentional automatic release. In this case it is possible for the system to start up water pumps, open main valves etc. on the first detector alarm in order to be ready for immediate release if the other alarm conditions are being fulfilled. This reduces the time loss and also ensures a quick suppression of the fire minimizing the danger and damage. Also these functions can be achieved using the standard functionality of the TS1000 Fire Detection System and the communication wires already installed for the fire detection purposes.
In the case of power control it is possible to have a local alarm functionality where the system supervises the engine room of the power unit with dedicated detectors being able to detect e.g. fuel leakage or overheating at a very early stage which can be difficult to detect from the engine control system. Such detection information could be used to control the power output from the engine or for a total shutdown of that specific engine if the train is equipped with other engines in order to reach a relative place of safety for the evacuation of the passengers and crew. Such early detection also reduces the costly consequences by a fire in repair, stand still etc.

Figure 3 Integration of different safety systems and components

All of these controls and others (Figure 3) can be expected to be offered by the Fire Detection System as the communication wires already are installed for fire detection purpose and could simply be realized by adding the local remote I/O units necessary for the physical controls.

The integration principles above is proven in use not only in railway applications but also in Marine, Industrial and Military applications using the same basic solutions providing the implementation of the optimal level of safety in the most cost-efficient way required by the European Parliament and the Council of the European Union thru its European Directive for Interoperability.
Parking Brake Fires in Commercial Vehicles

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EXTENDED POSTER ABSTRACT

The NFPA 2010 “Fire Loss in the U.S.” reports 215,500 vehicle fires occurred in the U.S. during 2010, causing 310 civilian fire deaths, 1,590 civilian fire injuries and $1.4 billion in property damage [1]. How many of the vehicle fires involve commercial vehicles is not well defined, but we do know that approximately 15.5 million trucks operate in the U.S. logging 432.9 billion miles in 2006 [2], out of a total of approximately 250 million vehicles registered in 2010 according to the U.S. DOT.

This analysis will address the appropriate methodologies used to help determine the correct origin and cause of parking brake fires in commercial vehicles. Fire origin and cause analysis on commercial vehicles can be very challenging due to the lack of familiarity and understanding by the fire investigation community about the specific pneumatic and mechanical systems associated with foundation air brakes and with the spring applied parking brakes systems that are commonly found on commercial vehicles. This analysis will focus on typically heavier trucks, tractor-trailers, and buses equipped with air drum brake systems (rather than hydraulic disc or drum brakes, or air disc brakes) and dual wheel/tire combinations at the wheel ends (rather than the newer and rapidly growing wide base single wheel/tire specification).

This analysis will provide the origin and cause investigator a review of how foundation air brake systems and their associated mechanical parking brake systems typically work on commercial vehicles. It will discuss common parking brake configurations and explain how their pneumatic circuits work. It will also review typical axle and wheel end configurations to help familiarize the investigator with other potential causes of wheel end fires, and will review all of the mechanical inspection procedures recommended to determine if the fire was caused by operating the vehicle with the parking brakes applied. This extended abstract will also provide a discussion of typical fire patterns caused by parking brake fires to assist an investigator in making a proper origin and cause determination. It will also review all other potential fire causes and fuel loads at a typical wheel end. The poster presentation for this abstract will provide photographic examples of the various wheel end components associated with the parking brake system as well as illustrate examples of typical fire patterns produced by a parking brake fire.

INTRODUCTION / REGULATIONS

Air brake standards in the United States applicable to new vehicles are promulgated by the National Highway Traffic Safety Administration by authority of Department of Transportation. Regulations are incorporated into the Title 49 of the Code of Federal regulations, Part 571 titled “Federal Motor Vehicle Safety Standards” (FMVSS). Regulations and standards specific to air brakes are Standard No. 121, and more commonly referred to as FMVSS 121. These standards are written as performance standards and do not dictate the design required to meet the performance requirements. The overall performance requirements are for the parking brakes to work in the forward and reverse direction, hold the full gross vehicle weight rating (GVWR) on a twenty percent grade, or for tractors with three or more axles, resist a drawbar force of 0.28 times the gross axle weight rating for all axles (except the front steer axle) or for all other vehicles, resist a drawbar force of 0.14 times the gross vehicle weight rating [3].
Since this extended abstract is intended to give an investigator a very broad based background and understanding of air brake regulations and performance requirements, it will explain the primary function of all of the major components involved in a modern airbrake system. It will discuss axle configurations and wheel end bearing systems found on these vehicles. It will provide a discussion of how foundation S-cam brakes work including brake chambers, automatic slack adjusters. It will also explain the driver controls involved in setting and releasing a parking brake, and discuss the warning(s) available to the driver. It will also look at the effects that anti-lock brakes systems and traction control systems can have on the foundation brakes.

WHEEL END AND BRAKE HARDWARE DISCUSSION:
Typical hardware found at the wheel end of the rear axles of medium, heavy and severe service trucks and busses with air brakes consists of a hub and bearing combination that runs on a hollow spindle at the end of an axle assembly. The bearings are retained on the axle by various wheel end nut retention locking configurations allowing certain bearing endplay. The axle driving the hub is of a floating design in that it drives the hub by way of flange at one end of the axle shaft, and has no direct contact with the bearing, thus not carrying the load. This is in contrast to a semi-floating axle design in smaller vehicles where the axle shaft runs though the middle of the bearings and carries load. The hub is most commonly surrounded by a dual brake shoe and drum brake assembly referred to as the foundation brakes. The shoes expand to apply the friction material to the inside of the drum by rotation of an “S” shaped cam. The S cam is turned by way of a pneumatic diaphragm and push rod assembly. When the service brakes are applied, compressed air is allowed to enter a chamber with the diaphragm. The diaphragm pushes on a rod that turns the S cam and expands the brake shoes. Activation of the parking brake is accomplished by way of a spring replacing the pneumatic pressure in the brake chamber. During operation, the parking brake spring is held back with air pressure. The parking brake is applied by releasing the air pressure holding back the parking brake spring. This feature makes the brakes fail safe as the parking brakes apply automatically when there is insufficient air pressure present in the parking chamber to hold them off. The truck or tractor parking brakes are typically controlled by way of a yellow diamond pneumatic push-pull valve on the dash. Semi-trailer parking brakes are operated by a separate red octagon push-pull control valve that applies trailer parking brakes [5,6]. FMVSS standards require a visible red warning lamp in the instrument panel that advises the driver when parking brakes are applied. Some manufactures also offer an optional audible alarm that sounds if the vehicle is moved while the parking brakes are applied. Most 6x4 tractors in the U.S. (the most common tractor configuration) are equipped with parking brake chambers on both ends of one of the two rear axles and can be additionally configured with parking brake chambers on both rear axles if desired. Parking brakes are typically not used on front steer axles. Tractors and semi-trailers both are now required to be equipped with an Anti-lock Braking Systems (ABS). Traction Control System (TCS), Roll Stability Control (RSC), and Electronic Stability Control (ESC) options are also available from manufacturers. The effects these systems can have on the brake system are discussed in the “Determination of Cause” section below.

DETERMINATION OF FIRE ORIGIN:
The most commonly acceptable way of determining the root cause in any vehicle fire investigation is to follow the accepted procedures as described in NFPA 921. The process consists of first establishing the area of origin for the fire, and then determining the cause, which are the circumstances that bring together a fuel and an ignition source [4]. The area of origin is generally determined by an interpretation of the fire patterns left by the fire. It involves assessing the different amounts of damage to the various components involved; taking into consideration the progression of the fire which is determined by the various fuel loads and ventilation effects involved the physical properties of the various materials, and the dynamics of the fire itself.

In the case of a wheel end fire, it is best to analyze the fire and damage patterns on the basis of the individual wheel end components involved. Bearing failures are manifested by severe wear, scuffing, or even deformation of the wheel bearing(s), often with corresponding damage to the axle spindle. There are typically two bearing sets per wheel end, and the damage can be observed in either one or both. The outer wheel bearing is often the first to experience damage if lack of lubrication is involved.
due to the typical geometry of tapered wheel ends. This bearing damage should then also correspond to a radial heat pattern on visible on the exterior of the wheel hub around the bearings. The heat patterns from the hub should also then correlate to preferential heat damage to the outer wheel in applications with dual wheels. The outboard side of the outer wheel will also show more damage than the inner side because of its proximity to the bearings.

Brake fires generally will not significantly affect bearings and wheel hubs. In a brake fire, these components are usually unaffected, especially when the hubs are made of cast iron. Aluminum hubs may show some minor melting due to the external heat. The primary heat patterns observed in a brake fire are an overheating of the brake drum in the area where the brake shoes make contact with the drum. The friction material on the brake shoes may, depending on its composition, show areas of melting, scuffing, high wear, or even a small layer of ash around the edges of the friction material. It is also common to find the return springs have annealed and lost their tension. The overheating of the brake drum should also correspond with overheating of the inner wheel. The inside of the inner wheel will be the most severely damaged, followed by its outside surfaces, then the inside of the outer wheel and so forth. This damage to the wheels will also correspond to the damage to the tires. The inside tire will be more completely consumed by the fire than the outside tire. The inner tire is the first major fuel source in a brake fire as the brake shoes and drums are components are located within the inner wheel. The inner tire burning will then leave a classic “V” burn pattern on the frame of the vehicle, and for a tractor drive axle, possibly also on the trailer, depending on the location of the fifth wheel. The classic “V” burn pattern will also be quite noticeable on the sides of semi-trailers and buses.

When evaluating heat patterns from a brake, it is of utmost importance to determine which wheel ends show signs of overheated brakes and if they correspond with the wheel ends equipped with parking brakes. Knowing if the vehicle is equipped with ABS, TCS, RSC, or ESC is also important, and its significance will be discussed in the cause section below.

Tire fires can happen when either a vehicle is operated with a flat tire [7], when road debris gets caught between two tires, or when the duals are both low on air and rub together. Tire fires rarely affect the wheel bearings, brake components, or cast iron hubs, but may show limited damage to aluminum hubs. Also, tire fires are most common on the inner tire as it is the most difficult for the driver to check during his pre and post trip inspections. During a wheel end fire inspection, if there are no signs of mechanical distress in the bearings and hubs, if the brake drums and brake components within the drums are unaffected by excessive heat, and if the wheels do not show heat patterns where they are bolted to the flange, then the probable fire origin is in the tire(s).

DETERMINATION OF CAUSE:
The discussion above should lead the investigator to realize that there are generally only three major competent sources of heat within a wheel end; brakes, bearings, and the tires, provided the vehicle was moving at the time of the fire initiation, and not subject to any incendiary or environmental causes. Since parking brake fires are the emphasis of this extended abstract, they will therefore be explained in more detail the other two alternatives.

When the fire patterns point to the wheel hub as the potential origin, the wheel bearings are the most common cause. They are either in good working order, or they are burn, melted, scuffed, and have affected the axle spindle. Leaking wheel bearing seals have not been found to be a fire cause. Bearing issues are not related to parking brake fires.

When the fire patterns point to a single tire as the origin, the fire was most probably run while flat, with debris, or under-inflated.

If the fire patterns point towards more than one wheel end as a potential fire origin, a parking brake fire cause should be considered, provided the suspect wheel ends are equipped with parking brake chambers. Since not all brakes are adjusted exactly the same, and since one side of the vehicle may
be cooler depending on wind direction, it is very common for one wheel end’s thermal damage or fire to progress further than the other(s). The investigator also needs to keep in mind that the parking brake system is independent of the service brakes, and that driving with the parking brakes applied is therefore not a malfunction of the service brakes. It is simply an oversight by the driver. The driver failed to release the parking brakes, and failed to notice the warning lamp on the dash.

ABS only releases the brakes, and therefore cannot be a cause of a fire, as a brake that is released does not create heat. TCS can apply the brakes, but only works on driven wheels and only on one side of the vehicle at a time. In a typical 6x4 tractor, only one side of the two rear axles are applied at the same time because of how these are configured with the sensors and modulating valves that apply the brakes. Modern and emerging electronic brake system enhancements such as electronically controlled RSC, ESC, and even newer automatic braking systems involving full stability control, adaptive cruise control, and collision mitigation do potentially apply certain selective brake sets. Thus there is a potential for failure modes in these applying and then not releasing selective service brakes (on wheel end equipped with or without spring parking brakes). No such failures are known or expected to have occurred and would also not be expected to correspond directly with the wheel ends with potential spring brake applications. This analysis additionally has not considered any unusual or rare failure modes in the brake system design that could be potentially envisioned to mimic a parking brake fire.

The parking brakes on typical tractors or straight trucks are applied by the driver by way of a push pull valve(s) located on the dash. Releasing the parking brakes prior to moving the vehicle is the driver’s responsibility. Failure to release the parking brakes and operating the vehicle results in the parking brake equipped wheel ends to overheat the brakes which then typically catch the inner tire on fire first, with the fire then progressing depending on how long it burns prior to extinguishment or lack of fuel.

CONCLUSIONS
Many modern commercial vehicles are capable of “driving-through” their spring applied parking brakes even though they comply with and meet all their applicable FMVSS 121 standards. The controls available to the operator allow the vehicle to be operated with the parking brakes applied, and operating the vehicle in this manner can cause a fire in one or more wheel ends of a commercial vehicle. Once the function of the foundation airbrakes and spring applied parking brakes is understood by a fire investigator, though tires are usually burned, the fire patterns left by a parking brake fire can usually be easily recognized and used to arrive at a correct causal determination.

KEYWORDS: commercial vehicle, truck, tractor, trailer, air brake, parking brake, brake fire, parking brake fire, wheel end, bearing, tire.

REFERENCES
Experimental Characterization of Automotive Materials in a Tunnel Fire

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KEYWORDS: automotive materials, midscale fire test, thermal degradation, tunnel fire

INTRODUCTION
The latest fire events (Frejus tunnel, 2005 and Channel tunnel, 2008) highlight an increasing need for tools to improve the safety of tunnels in case of a fire, and to better understand the physics of the fire source.

Since the early 2000s and the catastrophic fires in Mont-Blanc, Tauern and Gothard tunnels, in many countries worldwide, and especially in France, design heat release rate curves have been settled down. The latest PIARC document on the topic (see [1] for instance) reviewed the available experimental data from the recent research projects on fires in tunnels. However, the proposed design fire curves are still a global approach and rely on experimental data that are not close enough of real vehicle fire growth. On the academic research side, relevant works on thermal degradation of a specific material from micro to sample level scale are published (see [2]) but not yet usable from tunnel engineering point of view. To fill the gap between these academic research and the global approach derived for engineers, CETU is planning a research project. The preliminary step is presented in this article.

FIRE TESTS EXPERIMENTS
Fire tests were conducted in the midscale tunnel (approx. 1/3 scaling factor) at CSTB facilities [3]. The tunnel is 43 m long, with an hydraulic diameter of 2.17 m and a cross-section of 4 m² (see fig. 1).

Longitudinal ventilation is provided in the test tunnel through an extracting ventilator located at the downstream end. The fan can provide a longitudinal velocity up to 5 m/s – corresponding to 9 m/s in a tunnel at scale 1 with a 1/3 scaling factor.

(a) View of the test tunnel
(b) Cross-section view

Figure 1 Experimental installation.

For these experiments, only an heptane pool was used as the main fire source. The sizing was calculated assuming a full-scale HRR of 30 MW and applying Froude scaling laws [4]. Two ventilation regimes were considered: an over-critical velocity one corresponding to the usual smoke control scenario in one-way tunnels with longitudinal ventilation and a low velocity one to address stratification issues. For each of them, two tests were performed to assess repeatability.
From the original campaign on fixed fire-fighting systems [3], only measurement points to monitor temperature, air velocity, HRR and toxic gases concentrations were used for this series of tests. The point was to simplify the measurement set-up to speed up the acquisition process. Only visibility measurements and radiative flux upstream of the fire were ditched.

The tested materials samples were installed on two lines across the tunnel section (0.5m and 1.5m high) and at different location along the tunnel (one section upstream and 5 downstream of the fire). Figure 2 shows the sections where are located the samples and the temperature measurements.

![Figure 2](image)

**Figure 2**  Layout of the measurements section in the test tunnel. Samples are located at temperature (T) sections.

**TESTED MATERIALS**

Ten different materials that can be encountered in a vehicle driving through a tunnel were tested (see Fig. 3): tyre side-wall, bumper, seat stuffing foam, door insert (polyester), painted body, polystyrene, PMMA from lightings and tarpaulin. Three different kind of tarpaulin were used: a non-fireproof one and two levels of fire resistance.

![Figure 3](image)

**Figure 3**  Examples of the samples used
The samples, that do not exceed 10cm in size, are fixed on metallic cables across the tunnel (see fig. 4). Intentionally, this small size allows all 10 samples to fit on a single cable avoiding the near-wall region where the thermal stress due to the fire might less reflect the actual conditions in a full-scale tunnel. Also, by limiting the size we limit the possible interactions between the samples and they can then be considered as passive materials that do not increase the HRR of the fire.

Figure 4  Position of the samples inside the test tunnel

ANALYSIS
Analysing the data provided by the four fire tests done is not an easy task. Only a qualitative analysis of the temperature data, related to visual assessment of the samples, can be addressed. Figures 5 and 6 outline the samples at section 3m upstream of the fire and the temperature curve for both 0.5 and 1.5 m above ground.

Figure 5  Global view of the samples after the fire test (section 3m upstream).
Figure 5  Temperature curves at 3m upstream of the fire (0.5 and 1.5m above ground).

The samples located on the line at 1.5m above ground experience the backlayering from the fire as the test is performed with a longitudinal velocity below the critical value. The thermal degradation is quite complete even for the two models of fireproof tarpaulin. Those located at 0.5m above ground experience a rather constant temperature of around 30°C excepting during the last minute of the fire test where the temperature raises up to 60°C. Despite the quite low temperature level, the seat stuffing foam and the polystyrene show sign of a thermal degradation, may be due to extreme radiative flux at the very end of the fire test.

As a matter of facts, a more detailed analysis is required by correlating the visual assessments to the thermal degradation process, for well-known materials such as PMMA for instance. The way this database can be used to assess the temperature level reached in a real scale tunnel fire needs also to be addressed in further studies.

REFERENCES
Shall we consider new design fire scenarios in tunnel fires studies to take account of fast development of electro mobility?

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In the context of climate global warming, transport is one of the most important sources of atmospheric release of CO₂: indeed, according to the GIEC data, transport is responsible for the production of 15% of the world wide greenhouse gas emission. This implies that important improvements have to be made in order to reduce CO₂ emissions from vehicle tailpipes. As discussed in [1], new technologies are currently under development for minimising the transport ecological footprint. Electrical vehicles (hybrid, Plug-in Electric vehicles, full-electric vehicles) appear as one of the most interesting way because of the extremely low CO₂ production, even when considering the whole chain, from well to wheel relation [2].

Introducing new technologies may introduce emerging risks or is liable to modify risk profile, and therefore it is highly important to have an early assessment of those new risks all along its life cycle. This enables to appropriately size prevention and protection measures and prevent from unjustified safety related use restrictions eventually acting as regulatory barriers against market development. A well known example in France was provided with GPL cars that were banned from many underground infrastructures because of the explosion risk at the tank level that was not correctly treated in early phases of LPG car development in this country. To ensure that electrical cars will not encountered the same restriction, it is crucial to evaluate the different associated risk before the mass diffusion of those equipments. This paper proposes a first order global risk reflexion on the new risk introduce by electrical vehicle and required modification on the safety standards.

1. FEEDBACK

Several recent feedback examples shows that, for the few number of electrical car on the road, several fires was then observed:

- The electric taxi in Hanzhou in 2011, April the 12th.
- The fire of an electrical car in a private car park in the Connecticut in April 2011. One of the main particularities of this fire is that the fire restarts several days after the first intervention.
- The car fire inside a ferry that goes from Oslo to Copenhagen. While the vehicle was in charge during the travel that may have caused the fire. According to report [3], the electric cord however did not initiate short-circuiting, while the fire indeed started in the battery pack of the car.
- The EV bus fire that took place in Shanghai (China), in July 2011, involving LiFePO4 type of batteries.
- The vehicle fire that occurs several weeks after a crash test (November 2011). This case shows the ability of a fire to start because of small incident on the battery a long time ago.

On top of this feedback with electrical car fire, some major fires occurred recently in underground infrastructure as for example, the one in the car park under the “Place Vendome” in 2012, March the 8th. If there was fortunately no human consequence, the economical impact was then important because of the parking closure during several months. On top of that, the external consequences of this fire, this means smoke dispersion, generate a huge cloud outside the tunnel, Figure 1.
composition of this cloud, this means the toxic smoke component generates by the car fire is important.

Figure 1: Smoke cloud dispersion during the Place Vendome underground car park dispersion.

2. SPECIFIC RISKS FOR THESE NEW CARS

In the specific context of confined infrastructure such as tunnels or car park, general risks identified are increase due to confinement. Particularly, the fire development kinetic is increase because less energy is evacuated to the atmosphere. On top of that, for the same reason, thermal and toxic effects are more important as visibility decrease quickly that induces high difficulties in terms of evacuation. Because underground infrastructures are more and more used in modern cities, evaluation of consequences with standard cars comparison is crucial. This evaluation was made early in the development process of the electrical cars to prevent from dramatic economical consequences before its public expansion.

For such underground infrastructures, fire scenarios were developed based on fire tests achieved on classical vehicle [4]. Considering that energy release in case of battery fire is different from fuel fire and that produced gases in case of fire are different, new scenario should be required mainly to take account of the toxic potential of such a fire. Based on real scale fire tests with several Li-ion electrical cars [6], new representative fire curves were built. The electrical car curve and classic ones are compared on Figure 2. These curve shows that standard curves include experimental measurement for both electrical cars.

Figure 2: Fire curve comparison for standard and electrical cars.

Based on those curves, impacts of these new scenarios were evaluated using CFD modelling. Base on
the FDS fire code [5], thermal, toxic and visibility decrease impacts of those new design fires were evaluated for confined infrastructures as tunnel, car park and ferries. These computations show that, during the first 10 minutes that correspond to the time required for evacuation, the fire consequences are not increased in case of presence of an electrical car equipped with Li-ion battery. Figure 3 shows the vertical temperature distribution for the both technology fire cases 10 minutes after ignition in a section that goes through the fire. It indicates that temperatures imposed to people are the same for both cases.

![Figure 3: Temperature distribution in case of standard car fire (left) and electrical care fire (right) in a car park.](image)

The toxic gas distributions or more precisely HF concentration, are given on Figure 4 for the same both cases. Concentrations are plotted in a horizontal plane 1.5 m above the ground 20 minutes after the fire start, HF begin to be produce 15 minutes after the fire ignition, 20 minutes corresponds to its impact inside the structure. Conclusions are the same as those regarding temperature considering the HF toxicity threshold is around 600 ppm for non reversible effects after 10 minutes exposure.

![Figure 4: Temperature distribution in case of standard car fire (left) and electrical care fire (right) in a car park.](image)

It can then be concluded that, based on the real fire tests with Li-Ion electrical cars, this new technology does not generate additional risks in underground infrastructures compared with the accepted existing situation. More generally, based on the fire tests and those modelling, it can be concluded that electrical cars with Li-Ion technology does not generate additional toxic effect for smoke dispersion. There is also no modification in terms of fire spread. This conclusion still required to be extended to other cars with same battery technology but also to other technology used for electrical cars.

### 3. CONCLUSIONS

In this paper, a new fire curve for electrical vehicle is proposed both in terms of fire growth and toxic release. Those curves are currently only based on a few number of real scale fire tests and required to be extended with other experimental results. On top of that, only Li-ion batteries were considered while several technologies are distributed, fire risk requires several approaches. The fire CFD modelling consequences, based on those curves demonstrate that, for considered technology and specific cars, this new technology does not generate new risks for underground infrastructure. This clearly indicated that it could be developed with safety respect.
Finally, it can be conclude that, for safely build cars, the standard curve used for modelling car fire consequences in tunnel or other underground infrastructure is adapted for cars equipped with Li-Ion batteries.

Some other reflexions must still be managed regarding this technology such as production, transport or storage. If the specific configuration of the vehicle made the risk globally acceptable, the battery extracted from the vehicle could generate more dangerous fires to be considered: Is the commonly used curve for hazardous goods in tunnel includes a truck of batteries?

**KEYWORDS:** New energy carriers, electrical vehicle, design fire, CFD modelling

**REFERENCE LIST**


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