Post-collision fires in road vehicles, a pre-study

Raúl Ochoterena[1], Fabienne Roux[1], Anna Sandinge[1],
Christoffer Nylander[2],
Mats Lindkvist[3], Ulf Björnstig[3],
David Sturk[4] and Mikael Skrifvars[5]

SP Sveriges Tekniska Forskningsinstitut

SP Rapport 2016:55

[1] SP Sveriges Tekniska Forskningsinstitut
[2] Consillium Marine & Safety AB
[3] Umeå Universitet
[4] Autoliv
[5] Borås Högskola

Post-collision fires in road vehicles, a pre-study

Raúl Ochoterena, Fabienne Roux, Anna Sandinge, Christoffer Nylander, Mats Lindkvist, Ulf Björnstig, David Sturk and Mikael Skrifvars

Abstract

Post-collision fires in road vehicles, a pre-study

The loss of human lives and body injuries as a consequence of post-crash fires either by smoke inhalation or due to burn injuries are unfortunately not uncommon. The literature indicates that fire events related to crashes are still a significant problem. The increased combustible load in newer vehicles is an important factor to be taken into account for the fire safety, as well as their potential to release toxic fumes while burning. Trends indicate that the survivable collision energy will continue to increase and, at the same time, the probability of post-crash fires rises with the collision energy. This means that the occupants of a vehicle may probably survive a high energy collision but will sustain severe injuries or death due to a post collision fire.

This report contains a pre-study where a literature survey about post-crash fires was done including statistics on the causes and dynamics of post-crash fires in road vehicles based on the literature, crash and incident reports as well as on interviews with medicine specialists. Further, a study about current fire legislation, environmental aspects of fires and a literature study on materials used for the manufacturing of vehicles and their relation to post-crash fires are included.

Results from this study indicate that fires in vehicles originated by a collision event are a problem needed to solve.

Key words: Post-crash fires, fire statistics, environmental impacts.

SP Sveriges Tekniska Forskningsinstitut
SP Technical Research Institute of Sweden

SP Rapport 2016:55
ISBN 978-91-88349-57-6
ISSN 0284-5172
Borås 2016

Contents

1 Introduction

The loss of human lives and body injuries as a consequence of post-crash fires either by smoke inhalation or due to burn injuries are not uncommon. For instance, a study published by Viklund et al[1] shows that 5 % of all fatalities in Swedish roads due to collisions in passenger cars, sport utility vehicles, vans and minibuses which took place between 1998 and 2008 occurred in burning vehicles. It is interesting to notice that the aforementioned statistics have the same proportions than other countries[2], such as in the U.S.A. where, on average, 31 vehicle fires are reported per hour, and these are responsible for around 300 deaths and 800 injured persons per year. Furthermore, these vehicular fires are responsible for 12 % of deaths, 8 % of civilian injuries and 9 % of the direct property damage attributable to all the reported fires. For the case of Sweden, the cause of death in one third of the reported incidents was attributable to fire only with no or limited trauma injuries. This means that in these cases the occupants did not die due to the combined effect of trauma and fire injuries, but for the effect of fire only.

The vast majority of fire deaths are caused by smoke inhalation and not by burns as it is popularly believed. Smoke incapacitates the occupants of a vehicle fast enough to impede their evacuation from the burning object before the fire spreads and totally engulfs it.

Fire can incapacitate or kill by reducing oxygen levels, either by consuming the oxygen, or by displacing it with other gaseous effluents. Even non-poisonous gases can be deadly when hot since these can cause burns in the respiratory tract[3].

During fires materials normally burn in under-ventilated conditions where combustion is incomplete and large amounts of toxic particles and gaseous substances are released to the environment. The fire consumes the available oxygen and the fire effluents are mixed with the remaining oxygen, making these toxic compounds readily available to the respiratory system of living beings.

Smoke is the term used to describe a wide assortment of dangerous constituents which individual or conjugated effects can be incapacitating or lethal. Smoke is indeed a generic term used to describe a collection of airborne pollutants composed by gases and particles. Smoke is produced when a material undergoes combustion or pyrolysis. The production of smoke does not necessarily require of combustion or oxygen but of temperatures high enough to decompose the affected materials by pyrolysis.

- Particles have gained importance during the last decades due to the supported concerns about the severe health repercussions when these are breathed. However, airborne particles are not a just a medical concern since their presence can reduce the visibility and challenge the evacuation from fire hazards. The importance of particles from fires resides in the fact that particles with similar composition but different size distribution can reduce the visibility complicating evacuation actions and, at the same time, being transported deep into the lungs when inhaled. In general it can be stated that particles with

[1] Viklund Å., Björnstig J., Larsson M., and Björnstig U., Car Crash Fatalities Associated With Fire in Sweden, Traffic and Injury Prevention **14**, 823–827, 2013.

[2] Ahrens M., U.S. Vehicle Fire Trends and Patterns, Marty Ahrens, NFPA Fire Analysis & Research Division, Quincy, MA, June, 2010.

[3] http://www.nfpa.org/press-room/reporters-guide-to-fire-and-nfpa/consequences-of-fire#fumes

relatively large sizes reduce the visibility and ultrafine particles represent majorly a health hazard.

- Vapours can condense forming liquid droplets which can have poisonous effects if inhaled or absorbed through the skin and mucous membranes.
- Gaseous effluents such as carbon monoxide, hydrogen cyanide or phosgene can be deadly or incapacitating even in small quantities. Carbon Monoxide associates with erythrocytes replacing oxygen in the bloodstream and hydrogen cyanide interferes with cellular respiration.

The large amount of fatalities following vehicle fires can be understood by the low fire performance of the materials used for vehicle manufacturing. Although there is a legislation specifying some minimum requirements with regard to fire performance of materials fitted in vehicles, the existing legislation is flaccid when compared to the fire safety regulations for the aeronautic, marine and rolling-stock sectors. For example, fire prevention requirements in buses[4,5] do not cover aspects such as the limitation of peak heat release rate, smoke yield and toxicity as done in regulations for trains, planes and ships.

Reducing fires in vehicles is strongly related to the survivability of the occupants against a collision event. Statistics show that occupants travelling on modern vehicles have a higher probabilities of surviving to a severe impact than of those travelling on vehicles with older technologies. This is however expected, the active and passive safety systems increase the survivability rate but these do not reduce the risks of a fire as a post-collision event.

In order to reduce the number of injuries and human fatalities associated to post-crash fires in road vehicles, it is necessary to study the causes of these lethal fires. Of particular interest are the ignition sources, vehicle types, fire dynamics and toxicology mechanisms which directly contribute to the loss of human lives, for instance, the dynamics and toxicity of fires due to upholstery and materials in passenger compartments or toxic gases due to fires in electric vehicles. New materials and traction systems (e-vehicles) introduces new toxic substances when burning – but intoxication by some of them could be reduced by using available antidotes – which make knowledge of these substances necessary.

This document reports a the findings with regard to the problems related to post-crash fires in road vehicles from a multidisciplinary point of view.

[4] Directive 95/28/EC of the European Parliament and of the Council of 24 October 1995 relating to the burning behaviour of materials used in the interior construction of certain categories of motor vehicles, 1995.

[5] UNECE Regulation No. 118: Uniform technical prescription concerning the burning behaviour and/or, the capability to repel fuel or lubricant or materials used in the construction of certain categories of motor vehicles, UNECE, Switzerland, 2012.

2 Fire legislation for road vehicles

The fire performance of materials used in the interior of certain types of road vehicles are regulated by the directive 95/28/EC and followed by the regulation 118 adapted from the Directive 95/28/EC and regulation 107.

The directive 95/28/EC stipulates three different flammability tests:

- Vertical burning rate of materials.
- Horizontal burning rate of materials.
- Melting behaviour of materials.

Directive 95/28/EC requires three types of flammability tests for interior materials in the passenger compartment: 1) horizontal burning rate of materials, 2) melting behaviour of materials and 3) vertical burning rate of materials. In the first test, five samples in the case of an isotropic material or ten samples in the case of a non-isotropic material, should undergo this test. Each sample is exposed to a low-energy flame for 15 s inside a combustion chamber.

The small ignition source is provided by Bunsen burner and the gas supplied to the burner shall have a calorific value near 38 MJ/m^3. The results are considered satisfactory, if taking the worst case, the horizontal burning rate is not more than 100 mm/min or the flame is extinguished before reaching the last measuring points. In the second test, a sample is placed in horizontal position and is exposed to an electric radiator. A receptacle is placed under the sample to collect the resultant drops and some cotton is put in this receptacle to verify if any drop is flaming. Testing 4 samples, for both faces, this tests is considered satisfactory if, taking the worst results, no drop is formed which ignites the cotton wool. In the third test, three samples in the case of an isotopic material or six samples in the case of a non-isotopic material should undergo this test. This test consists of exposing the samples, held in a vertical position in a holder, to flame. The burner should be positioned in front of, but below, the sample. The flame height should be adjusted to 40±2 mm. The results are satisfactory if taking the worst results, the burning rate is not more than 100 mm/minute.

Directive 95/28/EC is applied for vehicles carrying more than 22 passengers, not being designed for standing passengers or urban use. This regulation is based on the flammability requirements for buses in the USA[6] brought into force as Federal Motor Vehicle Safety Standard (FMVSS) 302 in 1972. Directive 95/28/EC became the UNECE Regulation N.118 in 2005[7], with updates since then, such as including a new test to determinate the capability of materials to repel fuel or lubricants in 2010.

This regulation has received much criticism[8] mainly because the tests might only be suitable for small ignition sources such as a lighter. For this reason, studies such as[9] have

[6] Flammability of Interior Materials, Standard No. 302 (1972) Federal Motor Vehicle Safety Standards and Regulation, U.S. Department of Transport.
[7] UNECE Regulation No. 118: Uniform technical prescription concerning the burning behaviour and/or, the capability to repel fuel or lubricant or materials used in the construction of certain categories of motor vehicles, UNECE, Switzerland, 2012.
[8] Digges, K.H., et al. (2008), Improving survivability in motor vehicles fires, Fire and Materials Conference, San Francisco, USA, 2007.

provided other methods for analysing the flammability of interior materials. The latest revision of Regulation N.118 that of 2012, includes the use of the test method ISO 5658-2[10], lateral spread in vertical configuration. The materials that passes this test are considered to also pass the vertical burning rate test and the melting tests. Also, this last version requires the same flammability tests to the materials in the engine compartments.

On the top of the flammability tests, The UNECE Regulation N.107[11] improved the fire protection of buses in Europe in 2001. This regulation N. 107 and its updates, cover different topics related to bus safety. The engine compartment requires no flammable soundproofing materials or material liable to become impregnated with fuel, lubricant or other combustible material. A partition shall be fitted between the engine compartment and any other source of heat. The use of alarms in the engine compartment is demanded since 2012. Fire extinguishers and first-aid equipment should be placed on appropriate locations. Buses shall be equipped with an alarm system detecting either an excess temperature or smoke in the toilet compartments, driver's sleeping compartments and all other separate compartments (added in 2012). The driver’s compartment shall be provided by acoustic and visual signal (added in the last updated in 2014) operational whenever the engine start device is operated.

On the top of the requirements on fire protection, Regulation 107 includes other specifications related to fire protection such as the insulation and protection of electric equipment, the need of the no flammable material near any source of heat, exits and emergency characteristics (e.g. number, position and width), driver’s compartment and interior lighting.

The following fire tests are used for examining the fire performance of materials employed in road and off-road vehicles.

2.1 Horizontal burning rate

This test stipulates the burning rate limits of materials in the occupant compartments of road vehicles such as cars, trucks, busses, tractors and machinery for agriculture and forestry.

There are several versions of this test in which although the same test equipment is used for all the tests, the evaluation criteria and minimum requirements differ among versions. Most of the automotive producers have their own evaluation criteria and minimum requirements. Some of the most common versions of this standard are the following ones: FMVSS 302, ISO 3795, Volvo STD 5031,19 (automotive), Volvo STD 104-0001 (trucks) and ECE Regulation 118, Annex 6 (buses).

2.1.1 Test procedure

---

9 Forsth, M., Modin, H., and Sundstom, B. (2011) A comparative study of test methods for assessment of fire safety performance of bus interior materials. Fire and Materials, DOI: 10.1002/fam.1116.

10 ISO 5658-2:2006, Reaction to fire tests – Spread of flame: Lateral spread on building and transport products in vertical configuration.

11 UNECE Regulation No. 107: Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction, UNECE, Switzerland, 2014.

The test is conducted inside a test chamber where the test specimen is mounted horizontally. The exposed side of the test champion is subjected to an impinging flame from underneath. The burnt distance and the time taken to burn the material is measured during the test. The result, the burning rate, is expressed in mm/minute.

The following products are typically tested according to the Horizontal burning rate method:

- Materials and composite materials installed in a horizontal position in the interior compartment.
- Insulation materials installed in a horizontal position in the engine compartment and any separate heating compartment.

2.1.2 Requirements

The minimum requirements for a approving the fire performance of a material according to this method are the following ones:

- FMVSS 302: Maximum burning rate is 101.6 mm/minute.
- ISO 3795: No requirement.
- Volvo STD 5031,19: Maximum burning rate is 80 mm/minute.
- Volvo STD 104-0001: Maximum burning rate 80 is mm/minute.
- ECE Regulation 118, Annex 6: Maximum burning rate is 100 mm/minute.

2.2 Melting behaviour

This test is described in the ECE Regulation 118, Annex 7 and is employed for evaluating the fire performance of materials meant to be used in coaches and buses. The standard evaluates if a material can contribute to fire propagation though the release of molten material.

2.2.1 Test procedure

The specimen in placed in a horizontal position under a hot radiator panel. A receptacle is positioned under the specimen to collect the resultant drops with some cotton fibres to verify if the molten dropped material can lead to ignition of the cotton fibres.

The following products are examples of materials that can be tested with this method:

- Materials and composite materials installed more than 500 mm above the seat cushion and in the roof of the vehicle.
- Insulation materials installed in the engine compartment and any separate heating compartment.

2.2.2 Requirements

The minimum requirements for a approving the fire performance of a material according to this method are the following ones:

- ECE Regulation 118, Annex 7: No drop which can ignite the cotton fibres is released from the material.

2.3 Vertical burning rate

This test is described in the ECE Regulation 118, Annex 8 and is employed for evaluating the fire performance of materials meant to be used in coaches and buses.

2.3.1 Test procedure

The test specimen is mounted vertically on a metal frame with three treads of cotton mounted across. A standardised flame is applied at the bottom of the specimen and the time for the material to burn and break the cotton tread is measured. The result, the vertical burning rate, is expressed in mm/min.

The following products are examples of materials that can be tested with this method:

- Materials and composite materials installed in a vertical position in the interior compartment.
- Insulation materials installed in a vertical position in the engine compartment and any separate heating compartment.

2.3.2 Requirements

The minimum requirements for a approving the fire performance of a material according to this method are the following ones:

- ECE Regulation 118, Annex 8: The maximum burning rate is 100 mm/minute.

2.4 Capability of materials to repeal fuel or lubricant

This test is described in the ECE Regulation 118, Annex 9 and is employed for evaluating the fire performance of materials meant to be used in coaches and buses.

2.4.1 Test procedure

The material is fixed under a metal cylinder filled with a standardised liquid. After 24 hours the liquid is removed and the amount of absorbed liquid is measured.

The following products are examples of materials that can be tested with this method:

- All insulation materials installed in the engine compartment and any separate heating compartment.

2.4.2 Requirements

The minimum requirements for a approving the fire performance of a material according to this method are the following ones:

- ECE Regulation 118, Annex 9: The increase of weight of the test samples shall not exceed 1 g.

2.5 Resistance to flame propagation for electrical cables

This test is specified in the standard ISO 6722 and is a part of the requirement document ECE Regulation 118 valid for buses and coaches. This method evaluates the fire performance of electrical cables.

2.5.1 Test procedure

The cable of affixed length is installed on a fixture at an angle of 45° with respect to the horizon. A small flame is applied to the cable and the burning time and the damaged length of the cable are evaluated.

The following products are examples of materials that can be tested with this method:

- Electric cables

2.5.2 Requirements

The combustion flame of insulating material shall extinguish within 70 seconds and a minimum of 50 mm insulation at the top of the test sample shall remain unburned.

3 Statistical data from post-crash fires

To obtain a good general overview of the recent post-crash fire statistics in vehicles, different databases were analysed for the years 2002 to 2014 and relevant literature was summarized. In particular, the FARS, CDS and NFIRS databases were compiled for the United States and compared to literature, data from Sweden was obtained through the literature and data from England was provided by the fire statistical services. Additional attempts to obtain data from Belgium and France unfortunately provided little usable information, and access to The Swedish Transport Administration database was unsuccessful due to technical complications. The data from the United States and existing literature for both the US and Sweden could however allow a reasonable overview of the available data and general situation.

The compiled data from the United States suggests that up to 3% of vehicles involved in fatal crashes have a related fire event, and that over 5% of fatalities occur in cars having caught fire, up to 1/3 of the deaths being directly caused by fire. This is in good accordance with existing Swedish data. According to the FARS data, fire events in fatal crashes and associated fatalities show an increasing trend, in particular in the last four years, even though car crashes become less frequent. Most car fires are due to frontal crashes and start in the engine compartment; however fuel tank fires tend to be more severe and deadly in comparison. Increased energy absorption leads to more severe fires. The toxicity of the fumes produced by the burning material is important. Databases contain valuable information, but the amount of missing data is an obstacle to the analysis, in particular when it comes to specifically post-crash fire data. Strict conclusions are therefore difficult to articulate, but the results are however interesting.

3.1 Databases – Methodology

- FARS – Years 2002 to 2014 were analysed. The data was downloaded from ftp://ftp.nhtsa.dot.gov/fars/. This database registers all fatal crashes reported by the police, and all cases were taken into consideration for this analysis (30 000 to 40 000 accidents a year). The files accident, vehicle and person were analysed. To select the person data for only MVIT occupants, the person types (PER_TYP) chosen were 01, 02 and 09. Categorizations were performed according the NHTSA methodology.

- CDS – CDS data was analysed for the years 2005 to 2014. All data was downloaded from ftp://ftp.nhtsa.dot.gov/NASS/. The CDS database analyses only a few thousand cases a year, favouring more severe crashes to analyse them in detail. The weighting of cases reflects the probability of selection of a specific crash and allows national estimates. Only CDS-applicable vehicles were taken into account (BODYTYPE 01-49), both unweighted and weighted. Since the fire data in particular is quite limited (a total of 459 recorded fire cases from 2005 to 2014, representing 53 000 accidents when weighted), the analysis was conducted for all years pooled together and not year by year. This database contains extremely valuable information but unfortunately little is related directly to post-crash fires and the high quantity of unrecorded data is an obstacle. The high variety of weights given to the accidents makes the weighted “national estimates” of poor quality.

- NFIRS – NFIRS data was analyzed for the years 2005 to 2013. This database is documented by the fire services on a voluntary basis but is considered to record more than 70% of all fire events in the USA. The files were obtained on CD-ROM, generously sent by NFIRS. Analysis of this data was based on the USFA methodology. Only highway vehicle fires were considered, meaning that the following criteria were chosen: Version 5.0 data, Aid Types 3 and 4 were excluded to avoid double counting of incidents, Incident Types 131, 132, 136 and 137 only, Mobile Property Involved codes 1 and 3. Due to quality issues for some of the years of the Puerto Rico data, it was decided to exclude them from the analysis for all years. Some specific cases were also taken out depending on the indications provided by NFIRS with each data year. Unknowns are apportioned according to the distribution of known cases. Since NFIRS does not cover the totality of fire cases in the US, the raw data from NFIRS is scaled up using a scaling ratio based on NFPA's yearly national survey. Different ratios are used for fires and civilian deaths.

3.2 Results

Due to increased traffic safety measures, the amount of vehicles and fatalities involved in fatal traffic accidents has been decreasing over the years in the United States. On the contrary, **fire events** in fatal traffic accidents show increasing trends, in particular from 2012 onwards as shown in Table 1. Digges (2004) noted that 2.9% of fatal crashes had a fire event associated in 2000, which was virtually unchanged from the 1990s where fire events ranged from 2.6 to 2.9%. However our analysis shows that the proportion of motor vehicle in transport (MVITs) catching fire in an accident has been of over 3% from 2011 according to FARS data (up to 3.3% in 2013). The proportion of fatalities taking place in these vehicles follows a similar increasing trend, being over 5% from 2012 onwards. Roughly 1/3 of these fatalities occurred in vehicles were fire was noted as the most harmful event, but it is unfortunately not possible to conclude that these fatalities are directly caused by the fire. As a comparison, Viklund et al. (2013)[12] reported that 5% of fatalities in passenger cars on Swedish roads (1998-2008) occur in vehicles with a reported fire event, 1/3 of these fatalities being directly caused by fire. Data from England (2009-2015) ranges around 22 to 24% of these fatalities being directly caused by the fire, which is slightly lower. This generally indicates that fires related to crashes in vehicles are still a significant problem.

Important to note is that the FARS data does not allow to directly determine if the fire started in the vehicle of interest, nor if the fire is a true post-crash fire. The percentage of pre-crash fires leading to fatal crashes is however expected to be very small, for example since the first harmful event is coded as being fire/explosion in less than 1% of the cases.

[12] Viklund Å., Björnstig J., Larsson M., and Björnstig U., Car Crash Fatalities Associated With Fire in Sweden, Traffic and Injury Prevention **14**, 823–827, 2013.

Table 1. FARS, total MVITs involved in fatal crashes, % of these MVITs catching fire and % of total fatalities occurring in these burning MVITs. Data from FARS, 2002-2014. The fatalities associated to the MVITs catching fire represent about 1400 to 1700 persons. Roughly 1/3 of these fatalities have occurred in a MVIT where fire is the most harmful event (less than 0.3% unknowns); it is however not possible to know if these fatalities are directly caused by the fire. Note: the fire entry combines no fire and not reported, which means that the proportion of unknowns is not known.

Year	Total vehicles involved	% Vehicles catching fire	% Fatalities occurring in vehicle catching fire
2002	58426	2,95%	4,54%
2003	58877	2,77%	4,30%
2004	58729	2,79%	4,20%
2005	59495	2,98%	4,71%
2006	58094	3,03%	4,71%
2007	56253	2,96%	4,60%
2008	50660	3,01%	4,50%
2009	45540	2,93%	4,58%
2010	44862	2,86%	4,47%
2011	44119	3,03%	4,77%
2012	45960	3,31%	5,17%
2013	45102	3,14%	5,24%
2014	44858	3,28%	5,36%

The significance of post-crash fires can also be observed in the NFIRS database in Table 2. According to NFIRS data for the years 2005 to 2013, the main causes for car fires are mechanical failure (43%) and electrical failure (21%), collision accounting for only 4% of all vehicle fires. However, when it comes to vehicles fire fatalities, collision is the leading factor, with 55%.

Table 2. Primary factor involved in ignition. NFIRS data, 2005-2013. The column "vehicle fires" gives the distribution of these factors of ignition for all vehicle fires, whereas the column "fatalities" focuses on the distribution when fatal cases only are considered. Around 50 to 60% of all cases have unknown entries, the percentages are thus based only on the distribution of the known factors after apportion.

PRIMARY FACTOR INVOLVED IN IGNITION	VEHICLE FIRES	FATALITIES
Mechanical failure, malfunction	43.3%	10.7%
Electrical failure, malfunction	21.1%	1.3%
Misuse of material or product	12.6%	13.1%
Other factors	7.2%	14.8%
Fire spread or control	7.6%	2.3%
Operational deficiency		
- *Collision*	*3.6%*	*55.2%*
- Other	3.2%	2.1%
Design, manufacture, installation deficiency	0.7%	0.2%
Natural condition	0.6%	0.3%

Even though car fires due to collisions are relatively rare, they play an important role when it comes to fatalities and should be studied thoroughly so as to lower this fire risk.
Taking a closer look to the FARS database, all **categories of vehicles** do not have the same probabilities of catching fire. Passenger cars and light trucks have similar rates, ranging around an average of 3%, the rates of passenger cars slowly increasing over the years, the one of the light trucks being more stable. Large trucks have a much higher rate, varying between 5 and 7%. The amount of large trucks involved in these accidents are however much smaller than passenger cars and light trucks, which could be an

explaining factor of the higher variability of the data over the years. It would be interesting to determine the leading mechanisms behind the higher fire rate for large trucks. Hazardous loads could play a role, as well as the extra fuel tanks built in these vehicles. Interesting to note is that the rate of fatalities occurring in burning vehicles is slightly higher for light truck vehicles (average of 5.2% for 2002-2014) than for passenger cars (4.6%), while it is much higher for heavy trucks (20.5%). This is due to the fact that heavy truck passengers rarely die in fatal crashes compared to the occupants of the other vehicle involved, unless there is a fire entry. As heavy trucks were not the main point of interest of this study, this question was not analysed any further, but would be of interest for later research.

Zooming in on the passenger cars and their increasing fire rates but focusing on the **model years**, no major difference could be seen between the car pool aged 0-4 and the one aged 6-10 with the FARS data shown in Figure 1. This would indicate that newer models do not *per se* lower the fire risk on the basis of this data, and that even though they generally speaking seem to have a better behaviour during the period 2009-2011, their fire rates have caught up again the ones of the 6-10 years in 2012. Interestingly, Digges[13] notes that the fire threat has increased for passenger vehicles in recent model years, specifically when it comes to frontal crashes and rollovers. In Digges[14] is stated that the combustible material has increased 10-fold in the last decades. The increase and change of properties of the combustible material has shifted the transformed the fire threat.

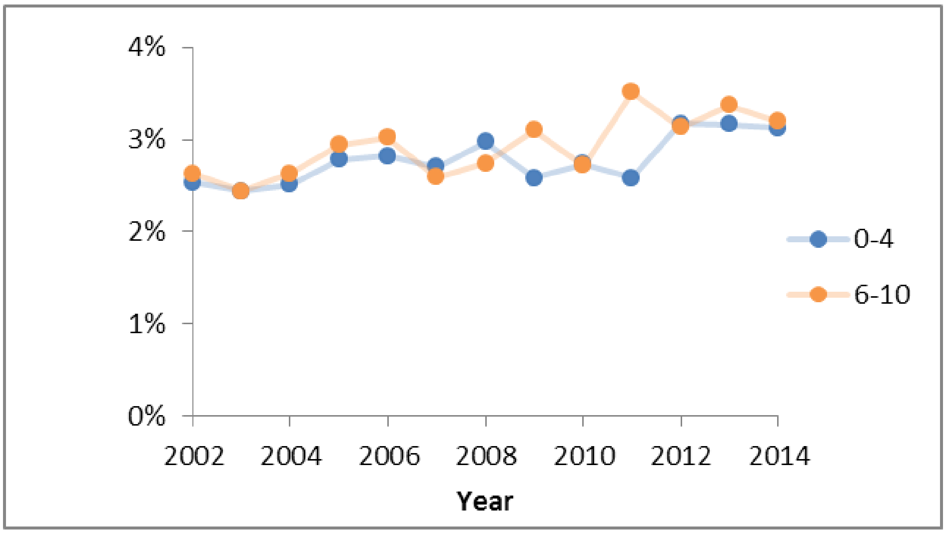


Figure 1. Fire rate of passenger cars, according to age category. FARS data, 2002-2014. This graph reflects the fire rate of passenger cars of a certain age category involved in fatal crashes. In blue: models aged 0 to 4 years, in orange models aged 6 to 10 years.

An analysis of the major **crash modes** in FARS shows that frontal crashes are overrepresented: 70% of all fires had a frontal initial / main point of impact. Rear, right and left have similar frequencies as shown in Figure 2. The fire rate of each crash mode

[13] Digges, K.H., Crashes that Result in Fires. *Proceeding of the 21st ESV conference*, paper number 09-0214, (2009).

[14] Digges, K., & Stephenson, R., Fireworthiness: a final report on the technology base. In ESV Conference, (2009).

is highest for the frontal impacts, and decreases following rear, right and left crashes. Interestingly, right and left impacts have different fire rates.

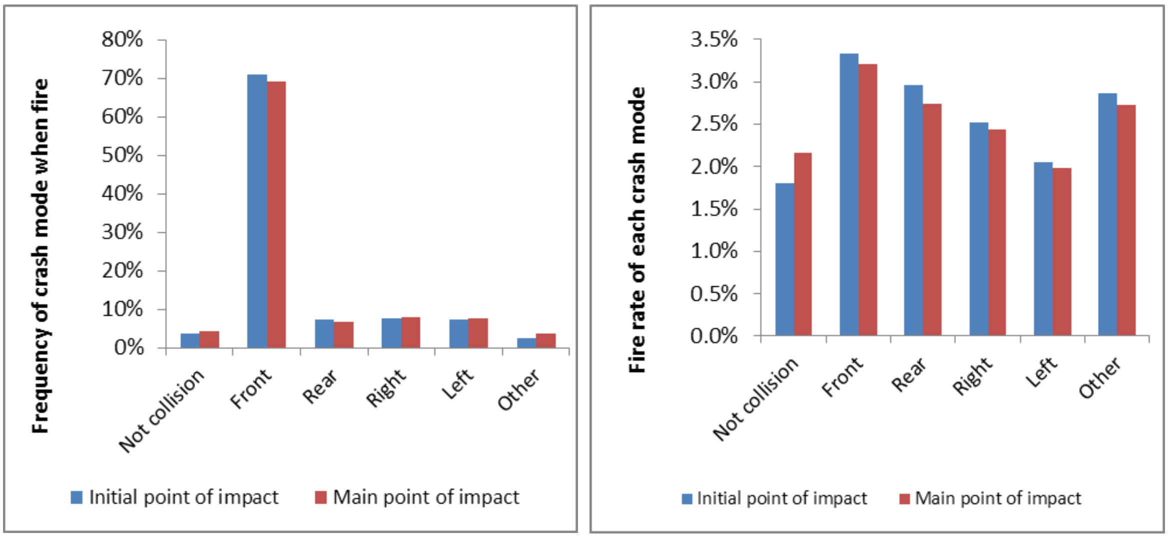


Figure 2. Primary factor involved in ignition. NFIRS data, 2005-2013. The column "vehicle fires" gives the distribution of these factors of ignition for all vehicle fires, whereas the column "fatalities" focuses on the distribution when fatal cases only are considered. Around 50 to 60% of all cases have unknown entries, the percentages are thus based only on the distribution of the known factors after apportion.

Rollovers seem to increase fire rates. From the total accidents with rollovers, 3.8% of the cases sustained a fire, whereas accidents with no rollover have a fire rate of 2.8%. This difference was shown to be even more drastic by Digges when only fire as most harmful event is considered, rollovers with a fire rate of close to 4% whereas the category without rollover has a fire rate of around 2.2%[15]. One can also note from the FARS data that rollovers are part of the accident event sequence in 23,8% of the fire cases. Digges[16] showed that rollover crashes could lead to higher fire frequency than other crash modes and states that the most frequent crash modes for major fires and fatalities are frontal and rollover[17]. Crashes which would be described as rollover crashes compared to other crash modes were however difficult to isolate in our analysis, which is why they have no category of their own.

Fire origin was analysed from both CDS and NFIRS databases. The engine compartment is found to be the place where most fires originate in both databases, with the fuel tank following in the second position. The passenger area is last. In particular, the CDS database shows that fires ignited by the fuel tank lead more often to major fires than minor fires as shown in Table 3. This can be set in parallel to the NFIRS data shown in **Error! Reference source not found.** indicating that even though most fires start in the ngine area, running gear and wheel area, the percent of fatalities vs fire events is much higher for fuel tank and fuel line originated fires. Digges also notes that about half of the engine compartment fires spread to the passenger area (major fire), and that there is generally more time to escape engine compartment fires than fuel tank fires, which could be a factor explaining their smaller relative fatality rates. In his analysis of rollover

[15] Digges, K.H. & Kildare, S., Fire occurrence in rollover crashes based on NASS/CDS. Presentation at SAE 2007 World Congress.
[16] Digges, K. H., & Stephenson, R., A Research Program in Crash-Induced Fire Safety. SAE International (2004-01-0475).
[17] Digges, K.H., Crashes that Result in Fires. Presentation at the 21st ESV conference (2009).

crashes, he showed that engine compartments are the main origin, with fuel tank fires more frequent for major fires[18]. The Swedish data from 1998 to 2008 analysed by Viklund et al[19]. recorded 7 fires started in the fuel tank and 5 only in the engine compartment, however half of the 32 fires had an undetermined origin. This small number of events does not allow comparison with the data from USA.

Table 3. Origin of minor and major fires. CDS data, 2005-2014, unweighted and weighted values. Note: up to 30% of the cases had a fire entry "unknown".

Fire occurrence	**Fire origin**	unweighted	weighted
Minor	**Engine compartment**	147	16364
	Fuel tank	4	780
	Passenger area	3	291
	Other	16	1389
	Missing	2	33
Major	**Engine compartment**	163	25595
	Fuel tank	47	2568
	Passenger area	6	469
	Other	24	3037
	Missing	47	2717

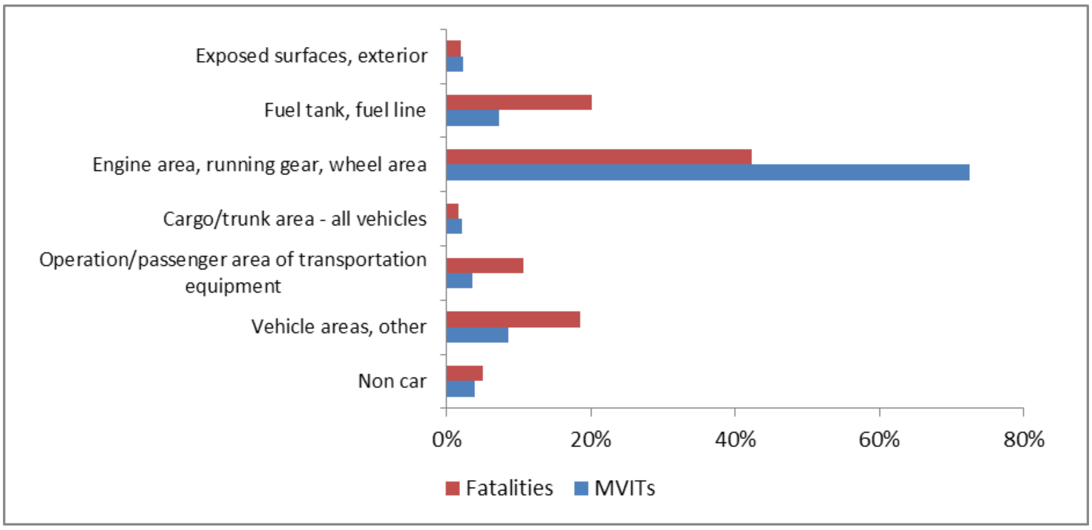


Figure 3. Area of fire origin for all MVITs fire cases and for all fatalities, when collision is the primary factor of ignition. NFIRS data, 2005-2013. Unknowns (8 to 15%) are apportioned.

Aggravating factors such as the **strength of the impact** or **entrapment** are important factors to take into account. Using the CDS database, one can see that fire probability increases with increasing energy absorption as shown in
Figure 4. The higher this energy, the more frequent and severe the fire cases are. The severity of the injuries increase between accidents, accidents with a fire, accidents combining both fire and entrapment (data not shown)[20].

[18] Digges, 2009, op cit.
[19] Viklund, 2013, op cit.
[20] Digges, 2009, op cit.

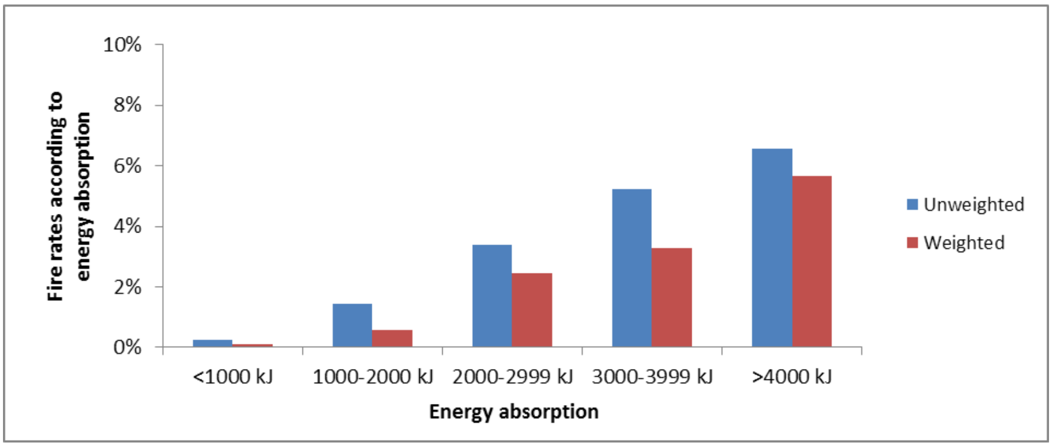


Figure 4: Fire rates in crashes according to energy absorption. CDS data, 2005-2014, unweighted and weighted. Note: up to 30% had a fire entry "unknown", and of the ones who had a fire, 50 to 60% had an unknown energy adsorption.

The fire threat should be addressed carefully. Real situation tests, which are not the standard tests performed when it comes to fire safety, have shown that the fire spreads faster when the engine has been running compared to when the engine is cold, that the kind of accident and severity affects the fire spread. In addition, the threat of toxic fumes could be greater than the risk from the flames, the ventilation potentially increasing smoke intrusion to the passenger compartment[21]. These fumes typically contain HCl, HCN, SO_2, aldehydes, isocyanates, VOCs (eg. Benzene), PAHs and PCDDs/PCDFs, all of them known toxic substances and a threat both to passengers and firefighters[22]. HF has also been measured for one car model[23]. Whether fumes or flames are the biggest threat could not be determined from the compiled data, but the data from Sweden and England tend to show that flames were the major cause of death and not the fumes. However the quality of this variable depends on the level of thoroughness of the medical examination, which is not known for the English data. Digges[24] performed crash tests and determined that once the fire penetrates the passenger compartment (which is the case for major fires) from either front or rear, about 2 minutes are given to evacuate all passengers. This means that knocked out passengers or passengers requiring extrication are extremely vulnerable. The importance of diminishing the toxic threat of the fumes and of gaining time is therefore vital.

This data and the literature indicate that fire events related to accidents are still a significant problem. The increased combustible load in newer vehicles is an important factor to be taken into account for the fire safety, as well as their potential to release toxic fumes while burning. Indeed, as crashes are expected to become more survivable

[21] Egelhaaf, M., & Wolpert, D., Post Collision Vehicle Fire Analysis. In22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV) (No. 11-0315), (2011).
[22] Lönnermark, A., & Blomqvist, P., Emissions from an automobile fire. Chemosphere, 62(7), 1043-1056, (2006).
[23] Lecocq, A., Bertana, M., Truchot, B., & Marlair, G., Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle. In 2. International Conference on Fires In Vehicles-FIVE 2012 (pp. 183-194). SP Technical Research Institute of Sweden. Borås, (2012).
[24] Digges, K., & Stephenson, R., Fireworthiness: a final report on the technology base. In ESV Conference, (2009).

with advanced technology, fire events might become even more relevant. Database analysis gives an interesting general picture of the situation, but unfortunately the difficulty of analysing these fire events more precisely, the lack of reporting and thus high proportion of unknowns are obstacles to an in-depth analysis. Different reporting methods between the databases and between countries make it difficult to compare the data on an equal basis. The determination of causal factors is also a challenge as so many variables need to be taken into account.

4 Survivability to a collision event with regard to fire

Reducing fires in vehicles is strongly related to the survivability of the occupants against a collision event. Statistics show that occupants travelling on modern vehicles have higher probabilities of surviving to a severe impact than of those travelling on vehicles with older technologies. This is however expected, the active and passive safety systems increase the survivability rate but these do not reduce the risks of a fire as a post-collision event. Statistics show that modern technologies increase the survivability rate of the occupants of a vehicle and partially reduce the extent of their injuries.

The aforementioned statistics shown in Figure 4 are clear in indicating that the probability of a post-collision fire event increases nearly linearly with the energy dissipated during the collision. Studies about the variation of crash severity and injury risk[25,26] where crash recorder data were used to determine average change of velocity and mean and peak accelerations of cars depending on their collision partner in both two- and single-vehicle crashes, on crash severity and injury risk indicate, not surprisingly, that higher change of velocities and mean accelerations are correlated to an increase increased average risk of an MAIS2+ injury .

Trends indicate that the survivable collision energy will continue to increase and, at the same time, the probability of post-crash fires rises with the collision energy. This means that the occupants of a vehicle will probably survive a high energy collision but will sustain severe injuries or death due to a post collision fire.

[25] Stigson H., Ydenius A., and Kullgren A., Variation of crash severity and injury risk depending on collisions with different vehicle types and objects.

[26] Ydenius A, Kullgren A. Influence of crash severity on injury risk in frontal impacts: A study based on real-life crashes with recorded crash pulses, Traffic Injury Prevention, 2006

5 Polymers and fire in vehicles – a literature review

Many types of polymers are used in more than 1,000 different parts of all shapes and sizes in an average car, these correspond to approximately 9 % of the car weight (Table 4). It has been estimation that the polymers contents of a automobile is 115 kg and petrol plus oils is 50 kg, i.e. a total of combustibles of 165 kg. Data from recycling of used automobiles show that automotive shredder residue could in average contain 100 kg plastics per vehicle. The amount of combustible material present in a standard automobile is thus in the range 150–200 kg. This is a rather large amount, which shows that plastics are a potential risk in car fires.

Table 4. Materials used in automobiles.

Materials used in automobiles	
Steel sheet	41 %
Plain steel	18 %
Aluminium	8 %
Cast iron	6.4 %
Zinc, copper, magnesium	2 %
Rubber	5.6 %
Plastics	**9.3 %**
Other materials*	9.7 %

**Adhesives/paints 3.0 %, glass 2.9 %, textiles 0.9 %, fluids 0.9 %, miscellaneous materials 2 %*

From the fire safety point of view, the fuel system and the gas tank, as well as the interior components (inner roof, seats, dash board, door covers) are most critical. To evaluate the fire risks related to the used polymers is complicated as there are many different type of polymers used in the car in many different components. (See Table 5) Additionally the polymers are used in different forms; plastic components, textiles and as composites. The plastic components are rigid objects with desired mechanical, barrier, thermal and surface properties. Depending on the use area, the material characteristics can vary a lot. The textiles are fibrous polymers which have been combined into textile fabrics, which often are used together with other materials. Comfort and sound insulation properties are the most important, while the mechanical properties are less important,

Without plastics, it is estimated that today's cars would be around 200-300 kg heavier. The resulting fuel savings are estimated at 0.5 litre per 100 km which represents 750 litres for a car with a lifetime of 150,000 km. Decreased fuel consumption and hence reduced associated pollution are the major benefits that lighter plastics parts bring to the automotive industry. Therefore it is evident that polymeric materials will be used in growing volumes in cars, and thus the fire behaviour of polymers in an impact situation is needed to be evaluated.

Although up to 13 different polymers may be used in a single car model, just three "families" make up some 66 % of the total plastics used in a car: polypropylene (32 %), polyurethane (17 %) and PVC (16 %).

Table 5. Plastics used in a typical car.

Plastics used in a typical car

Component	Main types of plastics	Weight in av. car (kg)
Bumpers	PP, ABS, PC/PBT	10.0
Seating	PUR, PP, PVC, ABS, PA	13.0
Dashboard	PP, ABS, SMA, PPE, PC	7.0
Fuel systems	HDPE, POM, PA, PP, PBT	6.0
Body (incl. panels)	PP, PPE, UP	6.0
Under-bonnet components	PA, PP, PBT	9.0
Interior trim	PP, ABS, PET, POM, PVC	20.0
Electrical components	PP, PE, PBT, PA, PVC	7.0
Exterior trim	ABS, PA, PBT, POM, ASA, PP	4.0
Lighting	PC, PBT, ABS, PMMA, UP	5.0
Upholstery	PVC, PUR, PP, PE	8.0
Liquid reservoirs	PP, PE, PA	1.0
Total		**105.0**

5.1 Description of materials commonly used in vehicles

5.1.1 Polypropylene (PP)

Polypropylene is a thermoplastic polymer used in a wide variety of applications. A saturated addition polymer made from the monomer propylene, it is rugged and unusually resistant to many chemical solvents, bases and acids.

Application: automotive bumpers, chemical tanks, cable insulation, gas cans, carpet fibres.

5.1.2 Polyurethane (PUR)

Solid Polyurethane is an elastomeric material of exceptional physical properties including toughness, flexibility, and resistance to abrasion and temperature. Polyurethane has a broad hardness range, from eraser soft to bowling ball hard. Other polyurethane characteristics include extremely high flex-life, high load-bearing capacity and outstanding resistance to weather, ozone, radiation, oil, gasoline and most solvents.

Due to the wide range of compositions possible, PUs have found extensive use in numerous commercial applications such as coatings, foams, adhesives, sealants, synthetic leathers, membranes, elastomers as well as in many biomedical applications. PUs are one of the most useful commercial classes of polymers which are widely used in both industry and in everyday life.

The repeating unit in PUs is the urethane linkage produced from the reaction of an isocyanate (–N C O) with an alcohol (–OH).

The most commonly used polyols are polyethers, polyester polyols or acrylic polyols. On the other hand, methylene diphenyl diisocyanate (MDI), hydrogenated MDI (H12MDI), toluene diisocyanate (TDI), isophorone diisocyanate (IPDI), xylene diisocyanate (XDI), and 1,5-naphthalene diisocyanate (NDI) are widely used diisocyanates in PU formulations.

The thermal decomposition of PUs (their degradation attributed to absorbed thermal energy) constitutes an important phenomenon from both a fundamental and a technological perspective;

Fundamental research has established that the thermal decomposition of PUs is a complex heterogeneous process and consists of several partial decomposition reactions. The decomposition of PUs occurs as a result of a multitude of physical and chemical phenomena and is not dominated by a single process.

The study of the decomposition of PUs is particularly difficult since they degrade with the formation of various gaseous products and a number of decomposition steps are typically observed in thermo-gravimetric analysis (TGA) experiments.

Applying increasing temperature to a PU system results in the thermal excitation of the covalent bonds in PU chains and once a critical temperature is reached, the PU starts decomposing and produces small molecules in the gaseous phase. The decomposed small molecules evaporate, diffuse into the flame zone above the polymer/air interface and mix with air to form a flammable mixture. When the concentration of this mixture and the system temperature crosses the flammability limit, it starts to burn. A part of the exothermic heat that results from the burning process is fed back to the condensed phase and accelerates the degradation of the PU, producing more volatile fragments and sustaining the combustion cycle. Finally, the combustion process ends with a material of different morphology.

Application: flexible foam seating, foam insulation panels, elastomeric wheels and tires, automotive suspension bushings, cushions, electrical potting compounds, hard plastic parts.

5.1.3 Poly-Vinyl-Chloride (PVC)

PVC has good flexibility, is flame retardant, and has good thermal stability, a high gloss, and low (to no) lead content. Polyvinyl chloride molding compounds can be extruded, injection molded, compression molded, calendered, and blow molded to form a huge variety of products, either rigid or flexible depending on the amount and type of plasticizers used. Polyvinyl chloride contains chlorine, which will lead to HCl formation upon fire.

Application: automobile instruments panels, sheathing of electrical cables, pipes, doors.

5.1.4 ABS

Acrylonitrile Butadiene Styrene is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The styrene gives the plastic a shiny, impervious surface. The butadiene, a rubbery substance, provides resilience even at low temperatures. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance.

Application: automotive body parts, dashboards, wheel covers.

5.1.5 Polyamide (PA, Nylon 6/6, Nylon 6)

Nylon 6/6 is a general-purpose nylon that can be both molded and extruded. Nylon 6/6 has good mechanical properties and wear resistance. It is frequently used when a low cost, high mechanical strength, rigid and stable material is required. Nylon is highly water absorbent and will swell in watery environments. The polyamides are used in engine components, and might be a fire risk in that environment.

Application: gears, bushes, cams, bearings, weather proof coatings.

5.1.6 Polystyrene (PS)

Naturally clear, polystyrene exhibits excellent chemical and electrical resistance. Special high gloss and high impact grades are widely available. This easy to manufacture plastic has poor resistance to UV light.

Application: equipment housings, buttons, car fittings, display bases.

5.1.7 Polyethylene (PE)

Polyethylene has high impact resistant, low density, and exhibits good toughness. It can be used in a wide variety of thermoplastics processing methods and is particularly useful where moisture resistance and low cost are required.

Another important area of development is in fuel systems. Again, this is an area which (for the safety of all) is a focal point for legislation, to conserve fuel and minimise emissions.

For more than a decade, all-plastics fuel tanks have been produced, by blow-moulding in ultra-high molecular weight high density polyethylene. Seamless, these one-piece tanks are much lighter in weight than their metal counterparts, and also, by their good mouldability, give more design freedom for locating tanks in difficult spaces.

It is estimated that some 90 % of all new cars in Europe have plastics tanks, and the technology has been exported to North America, where about 70 % of cars now use this system. In Japan, the market share is considerably lower, at about 7 %, but considerable growth is expected there also, to meet tighter fuel emission standards.

The development of fuel tanks presents a remarkable demonstration of the potential of plastics. Originally, tanks were treated internally to reduce the permeability of polyethylene. But, to meet tightening emission standards, particularly in the USA, multi-layer tanks are blow moulded, incorporating a layer of a high barrier polymer, and tie-layers to bond it to the structural inner and outer layers. A sixth layer is usually added, to re-use the scrap produced in manufacturing. Multi-layer extrusion technology is coming rapidly into the production of plastics fuel tubing, to reduce permeability to nearly zero and, where required, to include electrical conductivity.

Application: car bodies (glass reinforced), electrical insulation, fuel tank.

5.1.8 POM (polyoxymethylene)

POM has excellent stiffness, rigidity, and yield strength. These properties are stable in low temperatures. POM also is highly chemical and fuel resistant.

Application: interior and exterior trims, fuel systems, small gears.

5.1.9 Polycarbonate (PC)

Amorphous polycarbonate polymer offers a unique combination of stiffness, hardness and toughness. It exhibits excellent weathering, creep, impact, optical, electrical and thermal properties. Because of its extraordinary impact strength, it is the material for car bumpers, helmets of all kinds and bullet-proof glass substitutes.

Application: bumpers, headlamp lenses.

5.1.10 Acrylic (PMMA)

A transparent thermoplastic, PMMA is often used as a lightweight or shatter-resistant alternative to glass. It's cheaper than PC but is also more prone to scratching and shattering.

Application: windows, displays, screens.

5.1.11 PBT (polybutylene terephthalate)

The thermoplastic PBT is used as an insulator in the electrical and electronics industries. It is highly chemical and heat resistant. Flame-retardant grades are available.

Application: door handles, bumpers, injection components.

5.1.12 Polyethylene Teraphthalate (PET)

PET is mostly used to create synthetic fibres and plastic bottles. You may recognize it on clothing labels under the name "polyester."

Application: wiper arm and gear housings, headlamp retainer, engine cover, connector housings.

5.1.13 ASA (acrylonitrile styrene acrylate)

Similar to ABS, ASA has great toughness and rigidity, good chemical resistance and thermal stability, outstanding resistance to weather, aging and yellowing, and high gloss. Be careful not to burn this material. It will cause a toxic smoke.

Application: housings, profiles, interior parts and outdoor applications.

As a summary, it is evident that many different polymers are used in the car, and in order to evaluate the risks in a fire situation after impact, it is necessary to identify the polymer types which are used in the components which have the highest probability to be ignited in an impact situation.

5.2 Fire and polymers

The emissions from automobile fires reported by Lönnermark and Blomqvist[27] identified the components giving the highest risk to produce harmful fire effluents using small-scale fire tests.

The results of the small scale tests showed that many of the materials from the automobile contained nitrogen and that these were capable of producing hydrogen cyanide (HCN) and other nitrogen containing compounds. The materials identified to be the greatest potential source of harmful compounds was that present in the upholstered seats in the automobile. From this material (presumably PUR), in addition to nitrogen containing species, also hydrogen chloride (HCl) and sulphur dioxide (SO2) were detected. Other material that produced even higher amounts of HCl included that in the door panel and electrical wirings. It was noted that rather similar yields of HCl were produced independently of the combustion conditions (pyrolytic or flaming). This could be expected as it has been shown that, for e.g. PVC, dehydrochlorination occurs rapidly and almost quantitatively above 300 °C. The presence of chlorine in the material from the automobile indicated a potential risk for emission of chlorinated organic compounds, including dioxins. Hydrogen bromide (HBr) was not detected from any of the materials tested, although HBr could have been present in concentrations below the detection limit. One should note that brominated flame retardants are commonly used in components of modern automobiles.

The small scale tests were confirming in a full-scale automobile fire test (1998 class model), HCl, HCN and SO2 were produced in significant amounts. Analysis of volatile organic components showed that benzene is the most abundant compound. Isocyanates as well as polyaromatic hydrocarbons (PAH) were also produced.

The analysis of the smoke gases from the automobile fire showed that emissions with a potentially negative impact on the environment, or humans, are produced in significant concentrations. These emissions included HCl, SO2, VOCs (e.g. benzene), PAHs, and PCDDs/ PCDFs. Sources of chlorine in the vehicle for production of HCl and PCDDs/PCDFs included, most probably: upholstering materials, dash board components and electrical wirings, as indicated from the small-scale experiments conducted on selected materials from an automobile similar to that used for the full scale automobile fire. Comparisons with total emissions from fires in Sweden show that emissions of PCDDs/PCDFs from

[27] Op. cit.

automobile fires are significant. The emissions of PAHs from automobile fires during one year are also important in relation to total emissions.

Aldehydes and isocyanates were also found in the smoke gases, both compounds with well-documented short-term and long-term effects on humans. Other toxic compounds included: HCN, HCl, and SO2. These compounds have a direct effect on people and are of concern for rescue personal and others exposed to smoke from vehicle fires.

5.2.1 Testing and evaluation methods of polymeric material with regard to fire

For the evaluation of the fire behaviour of polymers in cars, testing is necessary to be done. The test methods are either aiming at:

a) Investigation the flame behaviour of the polymers
b) Identifying the decomposition products of polymers in a fire

These methods are well documented in the literature, and these are used routinely in the characterisation of polymers.

5.2.1.1 Flame retardant testing methods

Tests for evaluation of polymers flame retardancy can be divided into the following types:

5.2.1.1.1 Heat release tests/cone calorimeter

The cone calorimeter test is widely used to examine the performance of fire retardant polymers and it is one of the most advanced method for assessing the fire behavior of materials. The test apparatus contains an electric heater, an ignition source and a gas collection system.

In cone calorimetery, the thermal response of a sample depends on the applied radiation intensity. The principle of cone calorimeter experiments is based on the measurement of the decreasing O2 concentration in the combustion gases of a sample subjected to a given heat flux. The test gives a possibility to evaluate: (i) ignition time, (ii) heat release rate (HRR) and mass loss, (iii) specific extinction area, (iv) the ignitability; (v) the combustibility; (vi) the smoke production and (vii) the production of toxic gases.

Typically, the subject material is irradiated with a heat intensity similar to that experienced in a fire situation (25–75kW/m2) and the ignition, heat release and smoke release characteristics of the materials are measured.

The cone calorimeter brings quantitative analysis to materials flammability research by investigating parameters such as heat release rate (HRR), time to ignition (TTI), total heat release (THR) and mass loss rate (MLR). Heat release rate is the key measurement required to assess the fire hazard of materials and products as it quantifies fire size, rate of fire growth and consequently the release of associated smoke and toxic gases.

Cone calorimeter tests can be conducted in accordance with national and international standards including BS 476 (Part 15), ASTM 1356-90, ASTM E1354 and ASTM E1474, ISO 5660 [40].

5.2.1.1.2 Limited oxygen index (LOI) test

The limiting oxygen index (LOI) or oxygen index (OI) is a method for evaluation of the flammability of materials. The LOI measures the minimum oxygen concentration (in a flowing mixture of oxygen and nitrogen gas) required to support candle-like downward flame combustion of a vertically mounted specimen. Thus, the more oxygen required (higher LOI), the stronger the flame retardancy effect.

As air contains 21% O2, materials with an LOI below 21 are combustible, whereas those with an LOI above 21 are self-extinguishing. Hence, higher LOI values represent better flame retardancy and a smaller LOI represents a more flammable material. An LOI of greater than 26 is required for the qualification of self-extinguishing. It serves as a measure of the ease of extinction of the materials.

This method is suitable as a semi-qualitative indicator of the effectiveness of flame retardants during research and development stage, because the equipment is inexpensive and requirement for sample size is small. Real scale fire performance of a material cannot be accessed solely based on LOI value because of the low heat input and the simulated high oxygen concentration.

The LOI and OI can be determined by the ASTMD2863, ISO 4589, DIN 4102-B2, NF T51-071 procedures.

5.2.1.1.3 Ignitability tests (UL94)

UL-94 horizontal burning tests are the standard applied by the American Underwriters Laboratories for testing the flammability and fire safety of plastic materials used in devices and appliances. UL-94 tests classify plastics according to the way they burn in various orientations and thicknesses. UL-94 contains test procedures for both horizontally and vertically positioned test specimens in the form of rods.

The test is defined according to ASTM D 635, IEC 60695-11-10, IEC 60707, ISO 1210 (horizontal) and ASTMD635-77, ASTMD3801, IEC 60695-11-10, IEC 60707, ISO 1210 (vertical).

5.2.2 Chemical analysis of polymer decomposition products

Crucial information in this area is obtained from kinetic and mechanistic studies of thermal degradation and is a wide application area for thermal analysis methods, especially thermogravimetric analysis (TGA).

A more complete analysis of the investigated phenomena is possible if methods for identification of volatile products are applied, such as the techniques of pyrolysis–gas chromatography/mass spectrometry (Py–GC/MS), TGA-MS or TGA-FTIR analysis.

5.3 Flame retardants

There exist two approaches to achieve flame retardancy in polymers generally known as the ‘additive’ type and the ‘reactive’ type.

Additive type flame retardants are incorporated into polymeric by physical means. This obviously provides the most economical and expeditious way of promoting flame retardancy for commercial polymers. However poor compatibility, leaching, and a reduction in mechanical properties, are weakening the attraction for this type.

The application of reactive flame retardants involves either the design of new, intrinsically flame retarding polymers or modification of existing polymers through copolymerisation with a flame retarding unit either in the chain or as a pendent group.

At the present time new polymer design lacks sufficient versatility in manufacturing, processing and is uneconomical, due to the expense associated with qualifying a new material for use.

This leaves the modification approach the most favoured because covalently incorporating the flame-retarding unit in the polymer backbone imparts the flame retardancy permanently, and the original physical and mechanical properties are maintained.

The major additive type flame retardants are divided as following:

- Chlorinated paraffin, antimony oxide.
- Chlorine containing unsaturated poly(ester)s.
- Filler-like retardants.
- Intumescent flame retardant systems.
- Inherently flame retardant polymers.

Although halogen atoms (e.g. bromine or chlorine) form some of the most widely applied flame retardant materials, in particular for polymers used in composite organic matrices or in electronic equipment, they do have clear disadvantages: not least the potential to corrode metal components and, more pressingly, the toxicity of the hydrogen halide formed during combustion.

5.4 Mechanisms for flame retardants

All flame retardants act either in the vapour phase or the condensed phase through a chemical and/or physical mechanism to interfere with the combustion process during heating, pyrolysis, ignition or flame spread[28]. The incorporation of fillers mainly acts to dilute the polymer and reduce the concentration of decomposition gases. Hydrated fillers also release non-flammable gases or decompose endothermically to cool the pyrolysis zone at the combustion surface. Halogen, phosphorus and antimony act in the vapour phase by a radical mechanism to interrupt the exothermic processes and to suppress combustion. Phosphorus can also act in the condensed phase promoting char

[28] Chattopadhyay and Webster, Thermal stability and flame retardancy of polyurethanes, Progress in Polymer Science 34 (2009) 1068–1133

formation on the surface, which acts as a barrier to inhibit gaseous products from diffusing to the flame and to shield the polymer surface from heat and air.

The intumescent flame retarding mechanism involves material swelling when exposed to fire or heat to form a porous foamed mass, usually carbonaceous, which in turn acts as a barrier to heat, air and pyrolysis product. In an intumescent materials formulation, usually there is a char forming agent, a catalyst for char formation and a foaming (spumific) agent[29].

These two mechanisms are exemplified in Table 5Figure 5.

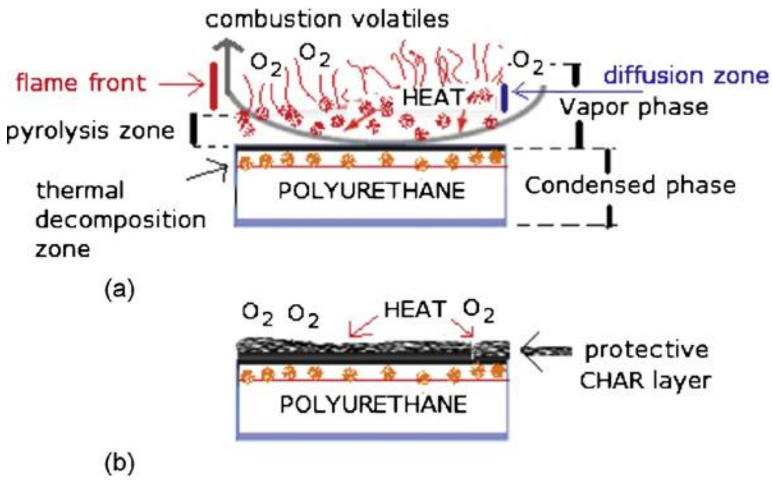


Figure 5. Typical process taking place during the combustion of PU in the absence (a) and presence (b) and of a intumescent flame retardant.

Polymers will become more and more important in car components due to their low weight, easy processability and good properties. In a fire situation in a car, all polymers will pose a potential health risk. As polymers are crude oil based organic materials they can act as fuel in a fire, which and further their decomposition will case the formation of hazardous gases and decomposition products. However, the fire retardancy of polymers can rather easily be improved by using flame retardants. Many flame retardants are toxic or problematic from the environmental point of view, but today many more environmentally benign flame retardant systems are under development, and will be introduced into the market.

The decomposition of polymers will form very hazardous gases and products. Chlorine in PVC will form HCl, while nitrogen containing polymers (polyurethanes and polyamides) will form HCN. Unfortunately these polymers have very good properties suitable for car components, so it is unlikely that these can be replaced by other polymers.

The fire situation of a car is complex, involving many combustible materials, and which proceeds rapidly with smoke generation. The role of individual polymers can have some impact on the first phases in a fire situation, and therefore the use of flame retardants in these polymers are important to give extra time for evacuation of passengers. During

[29] Lu and Hamerton, Recent developments in the chemistry of halogen-free flame retardant polymers, Prog. Polym. Sci. 27 (2002) 1661–1712.

later phases it is likely that the fire will proceed very rapidly, and polymer selection will not have a greater role in the fire behaviour.

6 The environmental impact of vehicle fires

In Sweden alone there are around 3500 automobile fires per year (3429 in 2014, according to the database of MSB). The question of whether these fires are a challenge to the environment has been taken up in relatively few studies. The drivers of their environmental impact can be divided in five groups: the type of vehicle and related emissions, the magnitude of the fire, the location of the burning vehicle, the amount and type of suppression medium used, and the containment and post-treatment measures. The analysis of emissions to air, water and soil are necessary to picture the complete extent of the potential damage.

Air emissions can typically be spread over great distances, relatively diluted, and subsequently deposited to soil and water systems. Lönnermark et al[30]. studied the gaseous emissions of car fires. They reported that the emissions of HCl, SO_2, VOCs (e.g. benzene), PAHs and PCDDs/PCDFs were significant. In particular, PAHs and PCDDs/PCDFs emitted from car fires are an important share of the total emissions of these compounds in Sweden. Also noted is that emissions of CO_2, CO, NO_x and SO_2 from car fires have been estimated as a minor share of the country's total emissions of these species by an earlier study by Persson et al.[31]. The species emitted from different types of vehicles are relatively similar, their amounts increasing with the amount of combustible. However, the fire environmental hazards of vehicles fuelled by new types of fuel such as ethanol, biogas, electricity, are still largely unknown. Hazardous loads can also prove challenging for truck fires, leading to very specific pollution events.

A number of studies have focused on the water runoff of vehicle fires. Conventional car fires are generally extinguished by water, but foam can also be used[32]. The runoff has proven to be heavily contaminated with metals and organic compounds and can be spread over great distances, reaching relatively high levels on a local scale. Typical contaminants are copper, zinc, lead, cadmium and antimony; toluene and benzene. Plastic residues such as acrylonitrile and styrene are also to be found[33]. This runoff, if not contained, will directly reach the environment where it can have acute but also chronic effects depending on the incident type. A specific challenge linked to vehicle fires are that they can happen in any location, which means that containment measures can be very challenging, their failure potentially leading to contamination of sensitive ecosystems. When happening on trafficked roads, the pressure to re-open the road can also lead to a minimization of the containment of the suppression media. Fire-fighters are often confronted with the question of extinguishing the fire, leading to high amounts of water run-offs, or letting it burn down under control, leading to increased air emissions.

Soil contamination is often very high but limited to a very local area. It can however serve as a pollution storage which can be released to water systems over time.

---

[30] Lönnermark, A., & Blomqvist, P. (2006). Emissions from an automobile fire. Chemosphere, 62(7), 1043-1056.
[31] Persson, B., & Simonson, M. (1998). Fire emissions into the atmosphere. Fire technology, 34(3), 266-279.
[32] Amon, F., McNamee M.S., Blomqvist, P. (2014). Fire effluents contaminants, predictive models, and gap analysis. Brandforsk project, SP report 2014-20.
[33] Noiton, D. (2001). The ecotoxicity of Fire Water Runoff-Part II: Analytical results. ESR, Fire Research Report, NZ Fire Service Commission Research Report, 18.

To conclude, few studies have been able to directly study the impact of car fires to the environment. Emitted toxic species have been largely reported for air, water and soil systems and could represent in some cases an important share of the pollution load of Sweden, such as for PAHs and PCDDs/PCDFs. Even though most car fires will present local and minor pollution events, specific situations in sensitive areas could lead to more serious consequences. Containment and appropriate treatment of the suppression medium are therefore important.

7 Summary and conclusions

This report indicates that fire events related to post-collision events are a significant problem. The increased combustible load in newer vehicles is an important factor to be taken into account for the fire safety, as well as their potential to release toxic fumes while burning.

Trends indicate that the survivable collision energy will continue to increase and, at the same time, the probability of post-crash fires rises with the collision energy. This means that the occupants of a vehicle will probably survive a high energy collision but will sustain severe injuries or death due to a post collision fire.

Indeed, as crashes are expected to become more survivable with advanced technology, fire events might become even more relevant. Database analysis gives an interesting general picture of the situation, but unfortunately the difficulty of analysing these fire events more precisely, the lack of reporting and thus high proportion of unknowns are obstacles to an in-depth analysis. Different reporting methods between the databases and between countries make it difficult to compare the data on an equal basis. The determination of causal factors is also a challenge as so many variables need to be taken into account.

The fire situation of a car is complex, involving many combustible materials, and which proceeds rapidly with smoke generation. The role of individual polymers can have some impact on the first phases in a fire situation, and therefore the use of flame retardants in these polymers are important to give extra time for evacuation of passengers. During later phases it is likely that the fire will proceed very rapidly, and polymer selection will not have a greater role in the fire behaviour.

Polymers will become more and more important in car components due to their low weight, easy processability and good properties. In a fire situation in a car, all polymers will pose a potential health risk. As polymers are crude oil based organic materials they can act as fuel in a fire, which and further their decomposition will case the formation of hazardous gases and decomposition products. However, the fire retardancy of polymers can rather easily be improved by using flame retardants. Many flame retardants are toxic or problematic from the environmental point of view, but today many more environmentally benign flame retardant systems are under development, and will be introduced into the market.

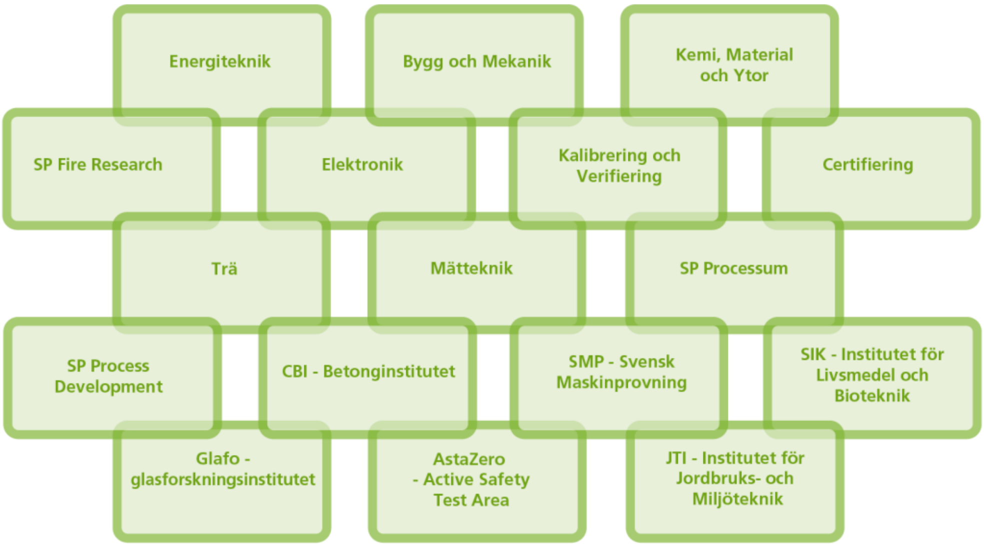
The decomposition of polymers will form very hazardous gases and products. Chlorine in PVC will form HCl, while nitrogen containing polymers (polyurethanes and polyamides) will form HCN. Unfortunately these polymers have very good properties suitable for car components, so it is unlikely that these can be replaced by other polymers.

Few studies have been able to directly study the impact of car fires to the environment. Emitted toxic species have been largely reported for air, water and soil systems and could represent in some cases an important share of the pollution load of Sweden, such as for PAHs and PCDDs/PCDFs. Even though most car fires will present local and minor pollution events, specific situations in sensitive areas could lead to more serious consequences. Containment and appropriate treatment of the suppression medium are therefore important.

To some of the most toxic gases as HCN and HF the emergency service may have a possibility to use specific antidote:s at an early stage to reduce the consequences – in combination with usual methods with oxygen therapy etc. given that they have knowledge about expected gases.

SP Sveriges Tekniska Forskningsinstitut

Vi arbetar med innovation och värdeskapande teknikutveckling. Genom att vi har Sveriges bredaste och mest kvalificerade resurser för teknisk utvärdering, mätteknik, forskning och utveckling har vi stor betydelse för näringslivets konkurrenskraft och hållbara utveckling. Vår forskning sker i nära samarbete med universitet och högskolor och bland våra cirka 10000 kunder finns allt från nytänkande småföretag till internationella koncerner.



SP Sveriges Tekniska Forskningsinstitut
Box 857, 501 15 BORÅS
Telefon: 010-516 50 00, Telefax: 033-13 55 02
E-post: info@sp.se, Internet: www.sp.se
www.sp.se

SP Rapport 2016:55
ISBN 978-91-88349-57-6
ISSN 0284-5172

Mer information om SP:s publikationer: **www.sp.se/publ**