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Communication

Human survivability in motor vehicle fires

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SUMMARY

Automobile fires are consistently among the largest causes of fire death in the United States (about 500 annually) and the U.S. motor vehicle industry and others have spent a significant amount of money in recent years studying this problem. The authors of this review have analyzed the auto industry reports, the scientific literature, and statistical data, and conclude that measures should be taken to improve survivability in automobile fires. The U.S. Federal Motor Vehicle Safety Standard 302 (FMVSS 302) was introduced almost 40 years ago to measure the flammability of interior materials, but improvements in the crashworthiness of automobiles and their fuel tanks and the increased use of combustible materials have changed the motor vehicle fire scenario significantly. In particular, the primary threat has changed from ignition of a small quantity of combustible interior materials by a lit cigarette, in 1960, to ignition of a large quantity of combustible interior and exterior materials by an impact-induced fire, at present. The authors therefore suggest that FMVSS 302 is no longer relevant to automobile fire safety and recommend improved standards based on objective criteria for fire safety performance (fireworthiness) at the system/vehicle level as is routinely done for crashworthiness. Copyright © 2008 John Wiley & Sons, Ltd.

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BACKGROUND

Deaths from automobile fires constitute the largest number of U.S. fire deaths outside of residences and rank overall among the top scenarios involving consumer products‡ [1, 2]. Of the 1.6 million fires reported each year in the U.S.A., one out of five (300 000) are vehicle fires [1–4]. Three quarters of vehicle fires are caused by mechanical or electrical failures during normal operation, but these are not particularly deadly because the occupants are usually able to escape. Less than 10% of vehicle fires are caused by collisions, but escape is more difficult in these situations, and collisions account for the overwhelming majority (60–75%) of vehicle fire fatalities [4, 5]. Vehicle fires cause some 3000 injuries and claim some 500 lives per year in the U.S.A. [2–4], about two-thirds of which are due to front impact, side impact, or rollover and about one-third of which result from other causes including rear impact [6–8]. The rapid progression of fire and incapacitation of passengers were contributing factors in two-thirds of vehicle fire deaths [4]. It has been suggested that the number of fatalities attributed to motor vehicle fires is a gross underestimate because of ambiguous reporting methods [2–4], but there is no doubt that motor vehicles are a major component of the fire death problem [1, 2]. Given the fact that motor vehicles cause numbers of fire deaths comparable to those from mattresses or upholstered furniture [1], it is somewhat surprising that vehicles are not facing comparable regulatory scrutiny [9–12], either in the U.S.A. or elsewhere.

The U.S. National Highway Traffic Safety Administration (NHTSA), a branch of the Department of Transportation (DOT), has a legislative mandate, under Title 49 of the United States Code of Federal Regulations, Chapter 301, Motor Vehicle Safety, to issue Federal Motor Vehicle Safety Standards (FMVSS) and Regulations to which manufacturers of motor vehicle and equipment items must conform and certify compliance. The first such standard was FMVSS 209, concerning seat belt assemblies, which became effective on March 1, 1967. A number of FMVS standards became effective for vehicles manufactured on and after January 1, 1968. Subsequently, other FMVS standards have been issued. New standards and amendments to existing standards are published in the Federal Register. These Federal safety standards are regulations written in terms of minimum safety performance requirements for motor vehicles or items of motor vehicle equipment. These requirements are specified in such a manner 'that the public is protected against unreasonable risk of crashes occurring as a result of the design, construction, or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur.' The philosophy of NHTSA in developing standards for crashworthiness is to define minimum safety performance requirements with pass/fail criteria based on objective measurements of safety performance.

The fire safety of motor vehicles is regulated by FMVSS 301 for fuel system integrity, which was first issued by the NHTSA in 1967 and FMVSS 302 for flammability of interior materials in passenger cars, multipurpose passenger vehicles, trucks, and buses, which became effective on September 1, 1972. Owing to the hazard fires create, and the speed with which fires can spread, it

‡NFPA statistics indicate that upholstered furniture was the item first ignited responsible for 560 fire deaths per year and mattresses or bedding were the item first ignited responsible for 410 fire deaths per year during the 1999–2002 period [1, Table 9]. Over the same period, vehicle fires were responsible for 496 fire deaths per year (and 383 of those fire deaths occurred with highway vehicles [2]). Cigarettes are consumer products that are often a source of ignition; they are responsible for fires that eventually cause abundant fire deaths (probably over 800 per year [1]) once other products are ignited.

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is obviously preferable to attempt to reduce the risk of crash fires occurring rather than to rely on potential rescue efforts, once a fire has started. This is the aim of FMVSS 301. The requirements of this Standard are intended to strengthen and to protect the vehicle's fuel system, so that, in a crash event, the chances of fuel leakage and, consequently, the chances of fire and of occupant injury will be reduced. Because of the highly flammable properties of gasoline and the fact that gasoline was the predominant fire load when the standards were issued, it was an obvious first choice as the source of combustible material in motor vehicle crash fires. FMVSS 301 has reduced the risk of impact-induced fires due to fuel tank rupture, despite the increase in the numbers of automobiles in use. However, the overall vehicle fire death rate has remained relatively constant over the past few decades, at least partially because of a 10-fold increase in the amount of combustible materials (especially plastics) used for interior and exterior applications.

It is important to point out that the FMVSS 302 test is virtually an international standard, as it has been harmonized with many equivalent designations. Regulations based on this test are in use, to various degrees, in many countries, using, among others, the following standards: ISO 3795, BS AU 169 (U.K.), ST 18-502 (France), DIN 75200 (Germany), JIS D 1201 (Japan), SAE J369 (automotive industry) and, dealing with plastics flammability, ASTM D 5132.

The intent of FMVSS 302, as far as flammability of materials, was to reduce deaths and injuries to motor vehicle occupants caused by vehicle fires, especially those originating in the interior of the vehicle from sources such as matches or cigarettes. FMVSS 302 is unusual among the NHTSA standards in specifying a requirement for a material of construction rather than for a vehicle or its occupants. At the time that FMVSS 302 became effective, Goldsmith [13] estimated that 30–40% of vehicle fires originated in the vehicle interior (passenger compartment and trunk). That percentage has decreased to less than 10% over the past few decades [14], as collisions have become more impact survivable, fuel tanks are better protected, and the amount of combustible materials has increased from some 9 kg (actually 20 lb) per vehicle in 1960 [15] to some 90 kg (actually 200 lb) in 1996 [16, 17]. Combustible plastics now constitute the major fire load (twice the weight and heat content of the gasoline) in a typical vehicle and are most often the material first ignited in an automobile fire [2–8]. In fact, ignition and burning of combustible plastics are the major causes of death in impact-survivable accidents [2–8, 13].

The FMVSS 302 test requires the use of a $10\,\text{cm} \times 36\,\text{cm}$ (ca. $4\,\text{in} \times 14\,\text{in}$) sample that is clamped around the edges, suspended horizontally above a Bunsen burner flame, and briefly ignited from below (Figure 1). The horizontal burn rate of the sample cannot exceed 102 mm/min (ca. 4 in/min). DOT/NHTSA periodically examines the relevance of FMVSS 302 [18] under a larger effort to examine each of the Federal Motor Vehicle Standards in Chapter 49 of the Code of Federal Regulations, Section 571. In the 1990s, the U.S. National Transportation Safety Board (NTSB) requested that the DOT review and coordinate upgraded material fire performance standards across all modes of transportation after concluding that the 30-year-old federal guidelines for trains were not useful in predicting the safety of vehicle interiors in a fire [19]. Automobile flammability was examined in detail, beginning in 1995, with an administrative agreement between DOT and General Motors (GM) Corporation to settle an investigation by NHTSA regarding an alleged defect related to fires in GM C/K pickup trucks [20]. Under the GM/DOT settlement, GM agreed to support NHTSA's efforts to upgrade FMVSS 301 standard governing fuel system integrity through the public rule-making process. In lieu of a recall of alleged defective C/K pickup trucks, GM negotiated an agreement with DOT to invest $51 million over a 5-year period in vehicle safety research, of which $10 million would go toward fire safety research with an additional $4 million provided to the Motor Vehicle Fire Research Institute (MVFRI) specifically for impact-induced fires

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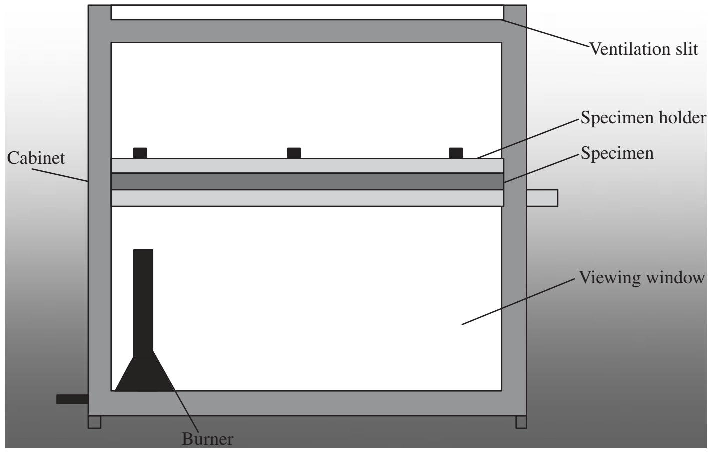

Figure 1. Schematic of FMVSS 302 fire test.

[21, 22]. Studies by GMs, in cooperation with the National Institute of Standards & Technology and FM Global, between November 13, 1996 and February 23, 2000 examined the effect of fire on post-crash survivability by conducting 11 automobile fire tests on previously crashed, late model vehicles [23]. The results of the tests and the $13.4 million research have been summarized in a 3 volume document prepared for MVFRI by FM Global [24–26].

RECENT RESULTS

As stated above, the results of the GM tests were analyzed [24–26] to determine the effect of materials of construction on passenger survivability in a post-crash vehicle fire. The authors concluded from the test reports that in front-end collisions where fire originates in the engine, compartment flames penetrate the vehicle interior within 10–20 min. Once flames penetrate the passenger compartment they spread several times faster than allowed by FMVSS 302, resulting in occupant death in 1–3 min. The calculation above of probable time to occupant death is based on the areal growth rate of burning interior materials necessary to achieve flashover conditions measured in certain vehicle burn tests [23]. The calculation formula used for linear propagation rate R (in m/s) in vehicle burn tests is

$$R=(Q/\mathrm{HRR})^{1/2}t_{\mathrm{fl}}^{-1} \tag{1}$$

where $Q=400\,\mathrm{kW}$ is the average heat release rate (HRR) of motor vehicle interiors at flashover, t_{fl} is the time between penetration of flames into the passenger compartment and flashover, and a HRR value of $430\,\mathrm{kW/m^2}$ is the mean peak HRR of 35 interior materials from an independent study [27].

In rear-end collisions, characterized in the test program by a gasoline pool fire, flames penetrated the vehicle interior through body openings within 2 min, after which flame spread by interior materials was 10 times faster than allowed by FMVSS 302 (see calculation above). Consequently, once flames penetrate the passenger cabin from either the front or the rear, death of all occupants

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will occur within about 2 min, due to the simultaneous effects of heat, burns, and toxic gases [19]. For other than front-end collisions, the survival time inside the vehicle is significantly less than 10–15 min [28] normally needed for first responders, such as fire and police departments, once notified of a crash, to reach a typical accident scene and begin rescue operations for trapped or incapacitated passengers. The rapid flame spread observed in vehicle fire tests, which is the dominant factor in fatal vehicle fires and the major cause of vehicle fire deaths [4], is due in large part to orientation, radiant heating by the fire, and the burning of molten plastic that drips away from the fire—all of which are absent from the regulatory test.

Subsequent to the GM study, and in response to the 1997 NTSB recommendations, studies were initiated by the NHTSA [27, 29–32], GM [33], the MVFRI [21, 22, 24–26], the National Fire Protection Association's Research Foundation [34] and other organizations [35–37] to investigate the fire performance of current automotive materials and to identify or develop test methods to rate fire performance and establish criteria that would significantly improve post-crash vehicle survivability. All these studies reached essentially the same conclusions:

1. modern fire tests can be used to quantify the ignitability and fire behavior of automotive materials to any desired level of accuracy;
2. these material-level tests in conjunction with full-scale vehicle fire testing over a range of material fire performance could be used to establish acceptance criteria that would guarantee sufficient escape time in a post-crash fire, and;
3. automotive plastics that pass FMVSS 302 offer little or no safety benefit to vehicle occupants in a post-crash fire compared with commodity plastics [36, 37] and they are much more flammable than aircraft cabin materials [37].

CALCULATIONS OF TIME TO FLASHOVER

Under the assumption that flame spread in vehicle fires is upward and/or turbulent, the flame spread rate is proportional to the two-third power of HRR, then

$$R \propto \mathrm{HRR}^{2/3} \tag{2}$$

and the time to flashover or survival time, t_{fl}, is proportional to the square root of the HRR at flashover, Q, and inversely proportional to $\mathrm{HRR}^{7/6}$, i.e.

$$t_{\mathrm{fl}} \propto Q^{1/2}/\mathrm{HRR}^{7/6} \propto Q^{1/2}/\mathrm{HRR} \text{ (approximately)} \tag{3}$$

This calculation that time to flashover is inversely proportional to the HRR of the component materials agrees with the results of full-scale tests conducted in commercial aircraft cabins [38, 39]. For the motor vehicle engine compartment and interior compartment, the heat release at flashover will be different, but for the present calculation they are assumed to be equal. In this case the relative increase in time to flashover for each compartment compared with the current vehicle configuration having $\mathrm{HRR}_0, t_{\mathrm{fl},0}$ will be on the order of

$$t_{\mathrm{fl}}/t_{\mathrm{fl},0} = \mathrm{HRR}_0/\mathrm{HRR} \tag{4}$$

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Thus, for a frontal impact with 10–15 min of fire growth in the engine compartment and 2 min of fire growth in the interior compartment before untenable conditions, a 10-min increase in time to flashover would require

$$HRR/HRR_0 = t_{fl,0}/t_{fl} = (10\text{–}15\ \text{min} + 2\ \text{min})/(10\text{–}15\ \text{min} + 2\ \text{min} + 10\ \text{min}) \approx 1/2$$

Consequently, to extend the escape time by 10 min in a frontal collision involving fire the HRR of under-hood and interior materials would need to be reduced by about a factor of 2 compared with that of current materials. A similar calculation for rear or side impact or rollover, in which fire penetrates the interior within 2 min and flashover occurs 2 min thereafter, gives

$$HRR/HRR_0 = t_{fl,0}/t_{fl} = (2\ \text{min} + 2\ \text{min})/(2\ \text{min} + 2\ \text{min} + 10\ \text{min}) \approx 1/4$$

Consequently, the HRR of under-hood and interior plastic materials should be reduced by a factor of about 4, in order to provide 10 min of additional escape time from fires caused by rear or side collisions or rollover.

DISCUSSION

The recent studies call into question the relevance and effectiveness of NHTSA motor vehicle fire safety standards with regard to the risk posed by automobiles in the context of flammable consumer items. The changing nature of motor vehicle fires is such that collisions are more impact survivable than in the past, but collisions cause most of the fatal motor vehicle fires. Moreover, plastics have now surpassed gasoline as the main fire load. Consequently, the FMVSS 302 motor vehicle fire standard fails to address the current vehicle fire scenario for the following reasons:

(1) Automobile fires account for some 95% of motor vehicle fires and some 92% of vehicle fire fatalities. The vast majority of fatal automobile fires result from collisions rather than from ignition of interior materials by a cigarette or small flame.
(2) Less than one-third of the approximately $20\,m^2$ [35] of combustible plastics, fabric, and foam surfaces installed in the vehicle interior are represented by the FMVSS 302 test, i.e. are upward facing in a horizontal orientation.[§] In fact, the majority of combustible surfaces in a motor vehicle are vertical or located on the ceiling, and the flame spread rate is many times greater for these orientations in a fire due to buoyancy effects and ignition of contiguous surfaces by flaming drops of molten plastic.
(3) Plastics that are exterior to the passenger cabin (i.e. in the engine compartment and body panels) represent a comparable fire load [16, 17] and fire hazard [30, 31, 36, 37] to the interior materials but are not required to pass any fire performance test. In fact, not even all passenger cabin materials are required to pass a fire test.
(4) The flame spread rate of combustible materials and fluids increases significantly in a vehicle fire that produces radiant heat, but this factor is neglected in the current regulatory test.
(5) It is impossible to use a material-level flame test, e.g. FMVSS 302, to predict the fire behavior of a vehicle without validating the material-level performance at full scale [38, 39].

[§]This calculation is based on materials in a midsize sedan, in which the floor, dashboard, rear deck, and seat bases are the only horizontal, upward facing surfaces.

CONCLUSIONS

Motor vehicle fire safety should be improved using objective measures of human tolerance to develop minimum performance requirements at the system level. In particular, regulations should address the magnitude and changing character of the motor vehicle fire problem by developing fire performance (fireworthiness) requirements for motor vehicles that will guarantee sufficient time for escape or rescue from a post-crash fire. Supporting standards should be developed based on human tolerance to the effects of fire, heat (as heat release is the most important factor in fire hazard [40]), smoke and toxic gases (especially carbon monoxide), which are well defined [24] and easily measured [24, 41, 42]. To have a meaningful effect on post-crash survivability, fireworthiness standards will guarantee that passengers find survivable conditions until rescue crews can arrive, in the event of restricted egress or incapacitation. Based on the analysis of emergency rescue operations, 10–15 min are needed for emergency personnel to arrive at the scene after an incident occurs [28]. An additional 5–10 min are probably required for rescue personnel to perform the rescue operations (e.g. the jaws of life), so that a realistic necessary survival time is of the order of 15–20 min after front, side, or rear impact. Based on an analysis of existing full-scale vehicle fire test data [24–26], fireworthiness can be achieved by the following means.

Full-scale fire tests can be conducted using vehicles that have been previously subjected to front, side, and rear impact testing for FMVSS. Standard pan fires (e.g. using several liters of heptane) under the engine compartment and rear of vehicle could be used to provide the ignition source and the time to untenable conditions in the passenger cabin recorded at passenger head level. A number of strategies involving 'fire restricting' materials,[¶] as well as other designs and systems have been identified in the full-scale test program [24–26] that are capable of providing 15–20 min of survivable conditions in the passenger compartment in a post-crash fire. These include but are not limited to the following:

1. Use materials with improved fire performance characteristics under the hood and in the passenger compartment to reduce the rate of flame spread in a post-crash fire. Calculations (see above) suggest that in order to gain 10 additional minutes of escape time in a post-crash fire caused by a frontal or side/rear impact the HRR of the plastics in flaming combustion would need to be reduced by a factor of 2 or 4, respectively, from the current value of HRR that is approximately $400\,kW/m^2$ [26, 27]. By way of comparison, an HRR value of $200\,kW/m^2$ (resulting from an HRR factor of 2 reduction) is typical of the fire performance of plastics that exhibit self-extinguishing behavior in vertical Bunsen burner tests, UL 94 V, of upward flame spread [43, 44]. A further decrease in the HRR of current automotive plastics to $100\,kW/m^2$ (i.e. a factor of 4 reduction) would lead to values typical of the fire performance of aircraft cabin materials [45].
2. Delaying fire penetration from the engine compartment to the passenger compartment by fire-hardening bulkheads, openings, and conduits between the engine and passenger compartments. Strategies include using fire-resistant materials (complying with a certain fire resistance rating in a standard time–temperature curve test) or intumescent seals around penetrations, under-hood fire blankets, flame suppression, and containment systems.

[¶] Fire restricting materials is the name given by the International Maritime Organization to materials with excellent fire performance that are permitted to be used for high-speed craft.

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3. Delaying the penetration of a fuel fire under the vehicle into the passenger compartment using crash hardening technology, fire blocking fabrics, fire/crash hardening of the fuel tank, fire suppression systems, etc.

In summary, motor vehicles are consumer items responsible for a major cause of fire deaths. This is due to the changing nature of vehicle fires over the past few decades, during which regulations have remained relatively static. Improved crashworthiness and increased use of lightweight plastics have made collisions the main cause of fatal fires, and rapid fire growth in the passenger compartment the main cause of death. Recent developments in fire testing technology, fire restricting materials, and fire protection systems have not been adopted by the automotive industry as they have by some other sectors of the public transport industry and by the construction industry. These improved technologies offer solutions to the vehicle fire death problem if regulations keep pace. Because fire deaths constitute only 4% of motor vehicle-related fatalities [46], a prudent path will include a cost/benefit analysis, lifecycle study, and an environmental impact study.

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