THE BASIS FOR A FLUID INTEGRITY NCAP RATING

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ABSTRACT

The frontal crash mode accounts for about half of the fires in FARS and NASS. Rollovers account for about 25% of the major fires in NASS and carry the highest risk of fatality in FARS fires. In NASS, the vast majority of fires that occur in frontal and rollover crashes originate underhood. Many of these fires eventually engulf the occupant compartment. Incapacitation and entrapment of occupants are important survival factors when underhood fires occur. Tests of several vehicles under operational conditions indicated that the surface temperature of the exhaust manifold and catalytic converter can exceed the ignition temperature of many underhood fluids. NCAP tests should include leakage measurements of all fluids. If leakage is observed, ratings could be assigned based on the amount and flammability of any fluid leakage. Since rapid egress is needed when fire occurs, the force required to open doors should be a basis for the safety rating, as well. Finally, there is technology on-the-road for electrical disconnects of the fuel pump and battery. These features should be evaluated as part of the NCAP test.

INTRODUCTION

FMVSS 302 regulates the flammability of interior materials in passenger cars, multipurpose passenger vehicles, trucks, and buses. It became effective on September 1, 1972. The intent of FMVSS 302 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. At the time that FMVSS 302 became effective Goldsmith estimated that 30% to 40% of vehicle fires originated in the interior (passenger compartment and trunk) [Goldsmith, 1969]. That percentage has decreased to less than 10% over the past few decades [Digges, 2005a and 2005 b]. Meanwhile, and the amount of combustible plastics and composites has increased from 20 lbs per vehicle in 1960 [NAS, 1979] to 200 lbs in 1996 [Abu-Isa, 1998 and Tewarson, 1997] and is over 300 lbs today [Tullo, 2006]. Combustible plastics constitute the major fire load (twice the weight and heat content of the gasoline) in a modern motor vehicle and combustion of these materials is the major cause of death in impact-survivable crashes [Bennett, 1990; FMRC, 1997; Ragland two ESV papers, 1998; USFA, 2002; FEMA , 2003; Friedman 2003 and 2005; Ahrens, 2005].

After FMVSS 301 was published in 1972, the focus of regulatory activity in vehicle fire safety has been on improving fuel tank integrity in a crash. The most recent upgrade phased in by September 2008 increased the severity of the rear and side crash tests. Many of the 1996 through 1998 vehicles analyzed already met the higher rear impact standard, based on the sample of vehicles tested [Ragland, two ESV papers, 1998].

The materials inside the occupant compartment that comply with FMVSS 302 provide little fire resistance when subjected to the heat load from a fuel tank or underhood fire. Burn tests from the GM/DoT research indicated that the occupant compartment became untenable within a few minutes of the flame penetration [Tewarson, October 2005 and Digges, 2007d].

In recent model vehicles, the vast majority of the fire cases in FARS are from fires in frontal crashes and rollovers. The frequency of these fires has increased during the past 10 years [Digges, 2008]. Research by MVFRI has shown that a number of innovations have been introduced by vehicle manufacturers to improve fire safety. Some of these improvements will be summarized in this paper. The purpose of this paper is to recommend that NCAP provide consumer information on these fire safety improvements in order to provide broader incentives for their use.

FIRES IN FATAL CRASHES BASED ON FARS

FARS is a census of fatal crashes that occur on public roads. FARS assigns the Most Harmful Event (MHE) to vehicles involved in crashes that involved a fatality. During this evaluation, passenger vehicles were analyzed including cars, pickups, SUVs, minivans and large vans. This excludes motorcycles or other 2 wheeled vehicles, and large trucks and buses. With the exception of rollovers, crash mode was defined using the location of principal damage or principle impact point which is the damage area on the vehicle that produced the most severe instance of injury or property damage. Rollover crashes are defined as an event where one or more vehicle quarter turns occurs regardless of the coded most harmful event. Most of the rollovers have damage to the front or sides of the vehicle. This damage may have been caused by impacts with fixed or non-fixed objects before or during the rollover. In some cases, these impacts may have been the cause of the fatality.

The figures to follow show the five year moving averages for the FARS years beginning in 1979 and ending in 2007. Figure 1 shows the FARS fire rate in passenger vehicles where at least one fatality occurred. The vehicle exposure per billion vehicle miles traveled (VMT) is the denominator. The upper (blue) curve represents fatalities in vehicles with fires. The lower (red) curve represents fatalities in vehicles with fire as the most harmful event (MHE). The fire as MHE applies to the vehicle not the persons in the vehicle. Consequently, there is no certainty that the fatalities were associated with the fire rather than the crash forces. However, death from the fire is more likely for this population.

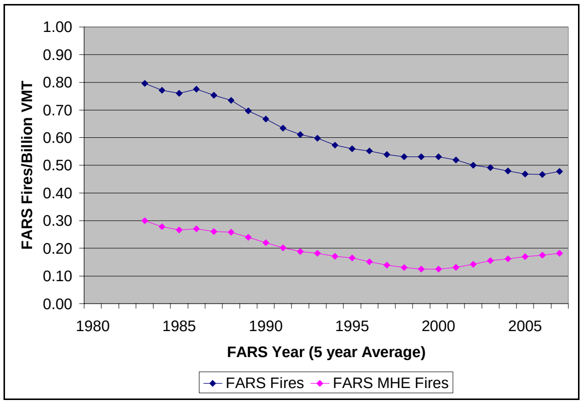

Figure 1. Fatalities in Vehicles with Fires and in Vehicles with Fire as the Most Harmful Event per Billion Vehicle Miles Traveled Annually - FARS

The distributions of annual fatalities and fatalities where fire was the MHE are shown in Figures 2 and 3.

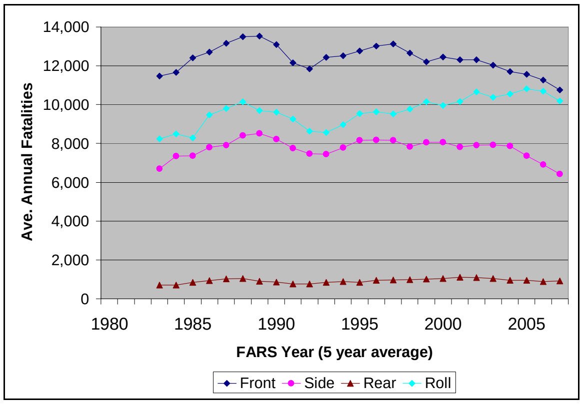

Figure 2. Average Annual Fatalities by Crash Damage Location – FARS 1979 to 2007

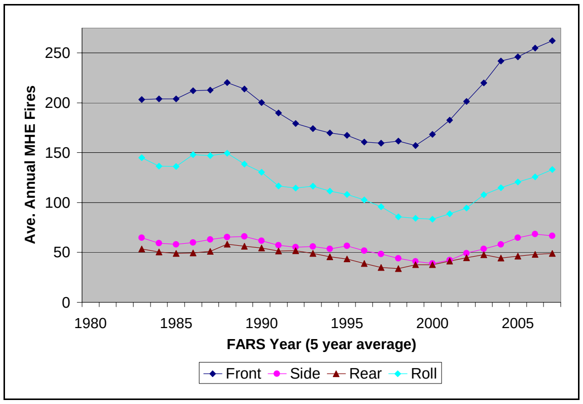

Figure 3. Average Annual Fatalities when Fire was Most Harmful Event by Crash Damage Location – FARS 1979 to 2007

Table 1 shows the distribution of fatalities in FARS years 2000 to 2007 where fire was the most harmful event. The distribution is broken down by the most severe crash direction and rollover is also identified if it occurred during the sequence of crash events.

The entrapment rate for FARS crashes fire as the most harmful event was 23% [Digges SAE 2005]. Based on FARS reported rescue times, 25% of the rural crashes require more than 24 minutes from crash to rescue. [Digges, ESV 2005].

Table 1. Distribution of Average Annual Fatalities when Fire was Most Harmful Event by Crash Type and Damage Location – FARS 2000 to 2007

Damage Location	No Roll	Rollover	Total
Non-Collision	0.6%	8.9%	9.5%
Front	37.6%	11.9%	49.5%
Right	11.2%	2.9%	14.1%
Rear	3.2%	1.4%	4.6%
Left	12.8%	2.8%	15.6%
Top	0.5%	3.1%	3.6%
Undercarriage	0.2%	0.7%	0.9%
Unknown	0.7%	1.5%	2.3%
Total	66.8%	33.2%	100.0%

FIRES IN TOW-AWAY CRASHES BASED ON NASS/CDS

NASS/CDS characterizes fires as either major or minor. A minor fire is an external fire that does spread to the occupant compartment or an occupant compartment fire that does not spread to the entire compartment or to other vehicle compartments.

NASS/CDS defines a major fire as the following situations:

- Total passenger compartment fire
- Combined engine and passenger compartment fire (either partial or total passenger compartment involvement)
- Combined trunk and passenger compartment fire (either partial or total passenger compartment involvement)
- Combined undercarriage and passenger compartment (either partial or total passenger compartment involvement)
- Combined tire(s) and passenger compartment (either partial or total passenger compartment involvement)

About half of the fires in NASS/CDS are major fires [Digges, 2007a] Major fires are more likely to produce serious burn injuries and are the subject of the analysis to follow. The data was published in a report prepared for MVFRI [Kildare, 2006].

Entrapment was recorded in 15% of NASS major fires where entrapment status was known [Digges, 2007b]. An examination of the crash severity at which entrapment occurs was investigated for all NASS cases, including those with no fire. For frontal, side and rear crashes with no fires, 50% of entrapments occurred at crash severities less than 17 mph. For far-side crashes the delta-V for 50% entrapment was 20 mph [Digges, ESV 2005a]. These results suggest that occupant entrapments can occur in relatively low severity crashes. For NASS entrapped occupants, 58% had AIS 3+ injuries [Digges, SAE 2005b]

Table 2 shows the distribution of NASS major fires by crash mode. As in FARS, the frontal and rollover crash modes comprise the largest percentages. Table 3 shows a further examination of the fire origin documented for these most frequent crash modes. The engine compartment is the most frequent fire source in both of these crash modes. Earlier studies reported that no fuel leakage was noted for most engine compartment fires [Digges, 2005b].

Table 2. Distribution of Major Fires by Crash Mode, Weighted and Unweighted Data NASS 1995/2005

Crash Mode	UNW	WGT
Front	51%	45%
Side	10%	6%
Rear	10%	8%
Rollover	21%	29%
Other/Unk	9%	13%

Table 3. Origin of Major Fires, Weighted and Unweighted Data NASS 1995/2005

Fire Origin	Front UNW	Front WGT
Engine Compartment	83%	90%
Fuel Tank	4%	1%
Other	13%	9%
Unk	4%	1%
	Roll UNW	Roll WGT
Engine Compartment	53%	50%
Fuel Tank	34%	46%
Other	13%	4%
Unk	9%	3%

An examination of rollover cases with fire origin in the engine compartment found that almost half suffered no significant damage prior to the rollover [Digges, 2007]. In most cases, the ignition source for the rollover fires could not be determined from the available case documentation.

There is no coding available for a flammable substance leakage other than motor fuel leakage. Consequently, there may be power steering fluid, brake fluid, coolant, window washer fluid, transmission oil, or oil pan leakage, which was responsible for feeding the fire but was not reported.

The majority of these engine compartment fires are reported as major fires. The cause of major fires is generally difficult to determine because the fire is so destructive to the evidence. Electrical faults and fluid spillage are two sources that have been demonstrated in crash tests.

Damage that caused leakage of power steering fluid was reported to cause engine compartment fires in two identical frontal crash tests [Santrock, 2005]. In these crash tests, the exhaust manifold was at operating temperature and the engine was running.

In another series of crash tests, an engine compartment fire was caused by electrical fault [Jensen, 1998]. The fire was unrelated to spilled gasoline or other engine compartment fluids, except battery acid. The fuel for the fire was provided by the plastic materials near the battery.

These test results suggest that factors that can not be identified by the NASS investigators may be associated with the large number of fires in which no fluid leakage was observed. Technology to prevent electrical faults and leakage of flammable fluids should be beneficial in reducing the incidence of engine compartment fires.

FIRES REPORTED IN STATE DATA

A study initiated by MVFRI examined the characteristics of fires in the police accident records of three states – Maryland, Pennsylvania and Illinois [Friedman, 2005]. The frequency of fires was found to be greatest in frontal impacts across all three states. All states reported a dramatic increase in the frequency and rate of fires in rollover crashes. This effect appeared to be independent of passenger car and SUV distinctions. The incidence of fires in rear impacts appears to be reduced compared to an earlier study by Malliaris [1991].

The Friedman Research Corporation also used state police accident data to examine the frequency of fires in pickup trucks of the same model but with different engines. The data indicated that for some full size pickup models the eight cylinder (V-8) engines had a higher fire rate than the inline six cylinder (I-6) engines [Friedman, 2006]. An obvious difference is the increased exposure of the exhaust manifold and catalytic converters in the V-8. However, the possible relationship between engine type and fire rate was not observed in a model of smaller pickups with V-6 and I-4 engines.

Another significant finding of this study was that pickups equipped with relay-type fuel cut-off switches had a higher fire rate in rollovers than those equipped with inertia switches [Friedman, 2006]. It was assumed that the relay switches used air bag deployment information that may not respond to a pure rollover.

GM TEST RESULTS – TIME TO UNTENABILITY

The GM/DOT Settlement research program in motor vehicle fire safety has been analyzed and synthesized by a team of fire experts led by FM Global. Of particular interest has been the analysis of eleven crashed vehicle burn tests. These tests subjected crashed vehicles to under-hood and spilled fuel fires of an intensity that could be possible after a crash. Three vehicles were subjected to under-hood fires with ignition sources either at the battery location or by the ignition of sprays and pools of mixtures of hot engine compartment fluids from a propane flame located in and below the engine compartment.

Two additional tests were conducted to evaluate countermeasures. The effectiveness of a fire retardant treatment of the HVAC unit was evaluated by tests of engine compartment fires in 2 vehicles with frontal damage. One of the vehicles was tested with the treatment and the other without.

A list of vehicles tested with engine compartment fires is as follows:

1. 1996 Dodge Caravan - front crash and fire started in the engine compartment;
2. 1997 Chevrolet Camaro - front crash and fire started in the engine compartment;
3. 1998 Honda Accord - front crash and fire started in the engine compartment;
4. 1999 Chevrolet Camaro - FR HVAC- front crash and fire started in the engine compartment;
5. 1999 Chevrolet Camaro - non-FR HVAC control-front crash and fire started in the engine compartment;

An in-depth analysis of these tests has been published [Tewarson, 2005, Vol 1]. The objectives of the analysis were to investigate the ignition and flame spread behaviors of engine compartment fluids and polymer parts, to assess time to flame penetration into the passenger compartment and to assess the creation of untenable conditions in the passenger compartment.

For the front crashed vehicle burn tests with ignition in and under the engine compartment, flame penetration time into the passenger compartment varied between 10 to 24 minutes.

Once the flame penetrated the passenger compartment, the environment rapidly become untenable. In some burns, the passenger compartment became untenable before flame penetration. The untenable conditions were due to heat exposure (burns) and exposure to combustion products (toxicity and lethality). The time between flame penetration and untenability of the passenger compartment varied from minus 2.5 to plus 3.2 minutes.

In general, polymeric parts in the engine and passenger compartments burn as molten pool fires with high release rates of heat, CO, smoke, and other toxic compounds, typical of ordinary polymers. Pool fires of the molten polymers are the major contributors to the vehicle burning intensity and contribute towards the penetration of flames into the passenger compartment. The fire retardant treatments of the polymer parts that were tested in the program proved ineffective in delaying fire penetration into the passenger compartment.

ENGINE COMPARTMENT TEMPERATURES

Additional testing has been conducted by Biokinetics and Associates, Ltd. to evaluate under-hood temperatures of different classes of vehicles [Fournier, 2004]. The results showed considerable difference between the maximum temperatures of different vehicles when operated under load. In a standardized uphill test, the maximum temperature measured on the exhaust manifold varied from a low of 241 ^{o}C for a minivan to a high of 550 ^{o}C for a passenger car.

FIRE PROPERTIES OF FLUIDS AND PLASTICS IN THE ENGINE COMPARTMENT

Tewarson has summarized the fire resistance measurements of fluids that are commonly found in the engine compartment. The flash point and hot surface ignition temperatures are summarized in Table 4.

The $\mathbf{T_{flash}}$ variable is the minimum temperature at which a fluid gives off sufficient vapors to form an ignitable mixture in an open cup. The $\mathbf{T_{hot}}$ variable is the minimum temperature of a hot surface to cause ignition of a fluid spilled on the surface. This variable requires a test that was developed by General Motors [Tewarson, 2005, Vol 2].

Table 4. Average Flash and Hot Surface Ignition Temperature of Underhood Fluids

Fluid	$\mathbf{T_{flash}}$ **(^{o}C)**	$\mathbf{T_{hot}}$ **(^{o}C)**
Motor Oil (Petroleum)	134	310
Motor Oil (Synthetic)	160	324
Gear Lubrication Fluid	154	325
Power Steering Fluid	188	312
Automatic Transmission Fluid	163	304
Brake Fluid	123	287
Antifreeze	116	506
Engine Coolants	110	518
Windshield Washing Fluids	32	

The Fire Safety Branch of the FAA and Galaxy Scientific Corp. performed flammability evaluations of 18 automotive plastics using a microcalorimeter at Trace Technologies, Inc. [Lyon, 2006]. The flammability of the underhood plastics tested was similar to the flammability of plastics from the passenger compartment. When compared to plastics used in the interior of aircraft cabins, the automotive plastics were several times more flammable. There was considerable variation in the flammability of plastics used under the hood. Two parameters used to measure flammability were the heat release capacity (HRC) and the total heat release (HR).

The heat release capacity (HRC) is the ratio of the specific heat release rate to the surface heating rate. The HRC is a flammability parameter that is a good predictor of fire performance and flame resistance. High values indicate higher flammability. Testing of 13 plastics used in aircraft passenger cabins produced an average value of 98 J/g-K. Plastics used in aircraft overhead compartments have an average HRC of 216 J/g-K.

The total heat release (HR) is obtained by dividing the maximum value of the specific heat release rate by the heating rate in the test. The HCR and HR values for typical automotive plastics are summarized in Table 5.

Table 5. Heat Release Capacity and Heat Release for Typical Underhood Automotive Plastics

Component Tested	HRC J/g-K	HR kJ/g
Brake Fluid Reservoir	1298	45.3
Resonator Intake Tube	1293	43.9
Battery Cover - black	1280	43
Front Wheel Well Liner	1250	45.3
Battery Cover -transparent	1106	42.9
Resonator Top	966	35.2
Radiator In/Out Tank	514	22.5
Engine Cooling Fan	400	18.6
Power Steering Reservoir	397	19.4
Hood Liner Face	101	7.9
Hood Insulator	96	5.2

TECHNOLOGY FOR FIRE SAFETY

A survey of the fire safety technology that was present in on-the-road vehicles was conducted by Biolinetics and Associates. Ltd. A database of 2003 model year vehicles was assembled and the technologies were documented in a database [Fournier, 2004]. Lists of available fire prevention technologies were summarized in subsequent papers [Fournier,, 2005; and Report R06-20, 2006].

The technologies that were present included:

- Check valves for the tank filler tube
- Roll-over leak prevention valves
- Shut-off mechanisms for electronic fuel pumps
- Crash sensing battery disconnects

It was observed that there was a difference in the extent to which fire safety had been incorporated into the vehicle design. For example, in selecting insulation material for underhood liners there were two orders of magnitude difference in the flammability properties from vehicle to vehicle [Fournier, 2006]. There was no relationship between the cost of the vehicle and the fire resistance of the underhood liner. This result suggests a lack of attention to the flammability of the material may have been a factor that precluded more fire resistant selections.

The analysis of state data suggested that some fuel cut-off systems were better in rollover than others [Friedman, 2006]

Fluid leakage in rollovers was another area where large differences were found among on-the-road vehicles. A research program by Biokinetics investigated and documented the technology in present day vehicles to prevent fuel leakage when lines from the fuel tank are severed [Fournier, R0-6-20, 2006].

Biokinetics conducted leakage tests on 20 fuel tanks to study the fuel containment technologies employed and their performance. The tests simulated a vehicle rollover by rotating a tank, filled to capacity, about an axis that when installed in a vehicle would be parallel to the vehicle's longitudinal axis. The tanks were rotated to seven discreet positions during the rollover simulation. None of the tanks leaked when all hoses were intact. In each position, the fuel system hoses were disconnected one at a time to represent a damaged or severed line and the resulting leaks were observed. The results of the testing showed that six of the tanks leaked in every orientation and ten leaked in some orientations. However, four fuel systems did not leak with one line at a time severed when subjected to all roll orientations. There was no relationship between the cost of the vehicle and the presence or absence of leakage prevention technology. The results of these tests are discussed in more detail in earlier papers [Fournier, R04-06c, 2004; Digges, 2005a].

DISCUSSION OF NCAP PROCEDURES

FARS, NASS and State data all indicate that the most fires in current vehicles originate in frontal crashes and rollovers. About half of the fires are in frontal crashes and a quarter are in rollover. The frequency of fires in rear impacts has been decreasing while fires in frontal crashes and rollovers have been increasing. State data indicates that the rollover fire rate has increased in recent years for passenger cars as well as light trucks and vans. Most major fires in NASS frontal crashes and rollovers originate in the engine compartment.

Many on-the-road vehicles incorporate technology to reduce fires that originate from electrical faults and fluid spillage. However, there is no way for consumers to know of these safety features. Simple modifications to the NCAP tests could provide valuable consumer information as well as rewards for incorporating fire safety technology. The initial focus of the testing should be on frontal crashes and rollovers.

MODIFICATIONS TO THE NCAP TEST PROCRDURE

FMVSS 301 requires a fuel containment test after the crash that subjects the vehicle to rollover attitudes. This test is called the static rollover test. The vehicle is placed in a fixture and rotated in 90 degree increments. At each increment, the fuel leakage is measured. There are no leakage requirements for fluids other than the motor fuel and none are measured.

The first modification to the NCAP test procedure we propose is to expose the test vehicle to the static rollover test before the crash test occurs. The vehicle would be tested in its operational state with all fluids at their recommended levels. The test would evaluate two fire safety features. The first would be a measurement of any leakage of a flammable fluid. The second would be an evaluation of any technology present to disconnect power from the fuel pump and the unfused battery-to-starter connection. . It is also recommend that the static rollover test be performed in 45 degree increments.

The second modification to the test procedure would be to measure the leakage of all fluids after the crash test and determine the degree to which the battery has been isolated. After the crash test, repeat the static rollover and measure all fluid leakage and determine the degree to which the battery is isolated in a rollover. The crash test should be performed with the battery fully charged and the electrical system connected. All of the fluids should be at their recommended levels. It would also be desirable to have the engine hot and running.

It is important for fluids to be present during the crash since they can provide substantial inertial forces to the container and the incompressible nature of these fluids can rupture the container. Engine coolant leakage should not be counted for the frontal crash, but may be counted for the side and rear crashes.

In the event insurmountable safety issues arise from testing with the flammable fluids present and the engine hot and running, less flammable fluids could be substituted as is currently done for the motor fuel in the FMVSS 301 tests. Under these conditions it may not be feasible to run the engine.

A third modification would be to evaluate the force required to open each of the doors. A rating system could be based on the door opening force required relative to the force that could be exerted by a small (5th percentile) female. See Appendix A of [Digges, ESV 2009] for a simple test methodology to determine this force level.

Finally, all fuel and vent lines leading from the tank should be cut or disconnected and fluid leakage should be measured when the vehicle is subjected to the static rollover test. This test would encourage the leakage prevention technology that currently exists in some vehicles to be more widely applied.

Fire safety star ratings could be based on the test results with points awarded for containment of fluids, the functioning of electrical disconnects and the force required to open each door.

CONCLUSIONS

The FARS data shows that in recent years, frontal crashes and rollovers have become an increasing fraction of the total highway deaths in which fire was the most harmful event. State data shows similar trends. An examination of major fires in NASS frontal, side and rollover crashes shows that the vast majority originate in the engine compartment. Fuel leakage was rarely documented in these cases.

It is probable that under-hood spilled fluids other than gasoline may be a principal source of the engine compartment fires. Tests of several vehicles under operational conditions indicated that the surface temperature of the exhaust manifold can exceed the hot surface ignition temperature of many underhood fluids. However, the frequency and extent to which these flammable fluids leak in crashes can not be determined from accident data because the fire destroys the evidence. Crash tests have shown that leaking power-steering fluid and battery faults are both possible sources of engine compartment fires.

Investigations of on-the-road vehicles has shown that extensive fire safety technology has been incorporated in some vehicles, but not others. There is some evidence of lack of attention rather than cost of countermeasures is an impediment to safety improvements.

The fire safety features of fuel pump and battery disconnect should be evaluated while the vehicle is exposed to a static rollover test before and after the crash test. In addition, the ease of egress from the vehicle should be evaluated after the crash test.

Finally, it is proposed that future NCAP tests include leakage measurements of all fluids. If leakage is observed, ratings could be assigned based on the amount and flammability of the fluid leakage. Fluid containment, electrical isolation, and ease of egress should be the basis for a star rating of fireworthiness.

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