

FIRE SAFETY PERFORMANCE OF MOTOR VEHICLES IN CRASHES

Kennerly H. Digges¹
R. Rhoads Stephenson¹
Paul G. Bedewi²

¹Motor Vehicle Fire Research Institute (MVFRI)
²FHWA/NHTSA National Crash Analysis Center –
The George Washington University
USA
Paper Number 422

ABSTRACT

The research reported in this paper is a follow-on to a five year research program conducted by General Motors in accordance with an administrative Settlement Agreement reached with the US Department of Transportation. In lieu of a vehicle recall to reduce vehicle vulnerability to post-crash fires, a research program was undertaken to provide knowledge to assist reducing the fire vulnerability for all future vehicles.

In this follow-on research project, GM agreed fund more than \$4.1 million in fire related research over the period 2001-2004. This paper summarizes the projects undertaken and the preliminary results.

Research projects that have been initiated include the following: (1) statistical analysis of field data; (2) assessment of state-of-the-art in fuel safety technology; (3) test and evaluation of fuel tanks exposed to fire and impact; (4) development of recommended practices for the fire safety of 42-volt electrical systems.

For the year 2001, there were a total of 1,657 fatal crashes in which there was a fire. This is about 2.9% of all fatal crashes. Analysis of FARS data indicates that the fire rates in cars has dropped by 43.7% and LTVs (pick-ups, vans and SUVs) by 59.7% since the 1979. In 2000, the fire rate for passenger cars was 5.14 fires/million vehicle years, compared to 6.39 for light trucks.

For the years 1997-2000 the NASS/CDS contains 228 cases with fires. In these cases, frontal crashes accounted for 51.3% followed by rollover (24.1%) and side (18.4). Rear impacts accounted for the smallest fraction – 6.1%. The most frequent origin for the fire was the engine compartment, accounting for 64.5%. The fuel tank accounted for 11.4%. There were a relatively large number of unknown sources – 17.1%. The most frequent object impacted before the fire occurred was another vehicle (41.2%). However, a variety of roadside objects made up

48.7%. Narrow objects such as poles and trees contributed more than 25%.

Plastic tanks of three different shapes were evaluated to fire and impact testing as required by ECE R34, Annex 5 and US CFR 393.67 (e)(1). The ECE R34 fire test appeared to produce repeatable results and all tanks demonstrated the capability to withstand the test. All tanks passed the ECE R34 impact test. The US CFR 393.67 (e)(1) requires the tank containing water equal to its rated weight of fuel to be dropped on its corner from a height of 30 ft. All new tanks passed the test. However, two of three tanks that had been in service for three years failed the test.

Research is now underway to identify state-of-the-art technologies in present day motor vehicles. Other research is oriented to developing test methods to assure the fire safety of materials used in vehicles with 42-volt electrical systems. The results of this research will be made public as it progresses.

INTRODUCTION

On March 7, 1995, the U.S. Department of Transportation (DOT) and General Motors Corporation (GM) entered into an administrative agreement, which settled an investigation that was being conducted by the National Highway Traffic Safety Administration (NHTSA) regarding an alleged defect related to fires in GM C/K pickup trucks [NHTSA 1994 and 2001].

Under the GM/DOT Settlement Agreement, GM agreed to provide support to NHTSA's effort to enhance the current Federal Motor Vehicle Safety Standard (FMVSS) No. 301, regarding fuel system integrity, through a public rulemaking process. GM also agreed to expend \$51.355 million over a five-year period to support projects and activities that would further vehicle and highway safety. Ten million dollars of the funding was devoted to fire safety research [NHTSA 2001].

Subsequent to the GM/DOT Settlement, GM agreed to fund an additional \$4.1 million in research related to impact induced fires. This latter research project was included under the terms of a judicial settlement. The fuel safety project objectives are defined by the White, Monson and Cashiola vs. General Motors Agreement dated June 27, 1996 [Judicial District Court 1996]. All research under the project will be made public for use by the safety community. The purpose of this paper is to provide an initial public

report on the projects that have been funded under this research program, along with results to date.

Research projects that have been initiated include the following:

1. A statistical analysis of field data to determine the frequency of fuel leaks and fires by model year and by other crash attributes.
2. A case by case study of fuel leaks and fires in NASS/CDS and an assessment of opportunities for reduction of vulnerability.
3. The assessment of the state-of-the-art technology to reduce the frequency of fires in motor vehicles and/or to delay the time for fires to propagate to the fuel or the interior of the occupant compartment.
4. The evaluation of fuel tanks of various shapes when subjected to fire and impact testing required by ECE or other government standards.
5. The development of recommended practices for the prevention of fires in vehicles equipped with 42-volt electrical systems.

The status and results of each of the above projects is summarized in the sections to follow.

STATISTICAL ANALYSIS OF VEHICLE FIRES

The occurrence of serious injuries and fatalities from fires has remained virtually unchanged over the past ten years. Based on data published by the NHTSA for the year 2000, there were a total of 1,657 (2.9%) fatal and approximately 5,000 (0.1%) injury crashes in which there was a fire [NHTSA 2002]. Of these, 328 crashes, totaling 552 fatalities, coded fire/explosion as the most harmful event. Between 1991 and 2000, the percentage of fire related fatal crashes has continued to range between 2.6 - 2.9% of all fatal crashes, and 0.1 – 0.2% of all injury crashes. Although driving exposure has increased over this time period, the occurrence of these fatalities and serious injuries warrants a more detailed investigation into the nature of these crashes.

Previous work has focused on the seriousness or severity of fire related casualties, including injury and fatality frequencies during impact induced car fires. Additionally, impact induced fuel leakage has also been studied, which may be another indicator of the performance and crashworthiness of fuel systems. Due to the continued occurrence of these events, there appears to be a necessity to reevaluate this topic as it applies to the current U.S. vehicle fleet. This includes looking at the effects of model year, crash

severity, fuel leak hazard, impact modes, and vehicle types. Previous studies have not focused on the vehicle mix, which has changed dramatically over the past decade. Of particular interest is the increasing population of light trucks (pick-ups, vans, and SUVs).

Several resources were used to determine the factors related to the actual occurrence and impact of fires in light passenger vehicles. These factors included (1) an investigation into the availability of fire related data from state, federal, private, and international sources, (2) a statistical analysis of national data from 1975-present, (3) a statistical analysis of selected state accident records from 1978-present. Results from item (2) will be presented here. Work under item (1) and (3) is still underway and results will be published at a later date, along with updates in the other areas.

Analysis of State and National Data from 1975-Present

Previously, Malliaris examined FARS 1975-1987 to understand certain trends in accidents associated with fire events [Malliaris, 1991]. The analysis reported in this paper further extends the Malliaris work to include the present vehicle fleet and provide a differentiation by vehicle type.

Malliaris also examined Michigan state data for the years 1978-1984 to assess fire rates and fuel leakage rates in police reported crashes [Malliaris 1991]. At present the state data study is being updated and applied to states other than Michigan. In 1990, Michigan discontinued reporting fuel leakage. Consequently, this condition could not be updated. Initial studies have confirmed a number of findings initially reported by Malliaris. The extension of the analysis to later years is now underway and will be reported when completed.

Fire Rates in Vehicles 0-4 Years Old Involved in Fatal Accidents

Figure 1 shows the fire occurrence for vehicles 0 to 4 years old at the time they were involved in fatal accidents. To be counted, a fire had to occur in the vehicle after the crash and a fatality had to occur in the crash. The fatality may or may not have been in that particular vehicle or caused by the fire. Figure 2 displays the same data adjusted for vehicle exposure. The exposure metric used in the figure is the number of registered vehicle years by vehicle class, given as million vehicle years or MVY.

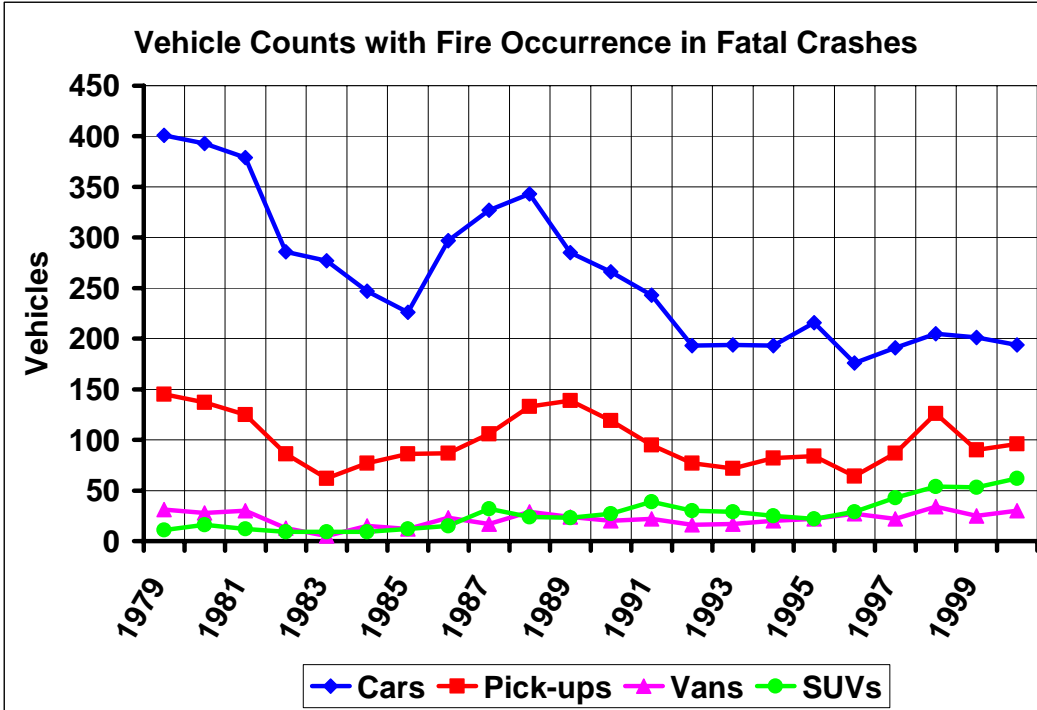


Figure 1. Frequency counts of vehicles involved in fatal crashes where a fire occurred in that particular vehicle (fatality did not necessarily occur in the vehicle with the fire). Data is from FARS 1979-2000, vehicle age is 0-4 years, and distributions are by vehicle type.

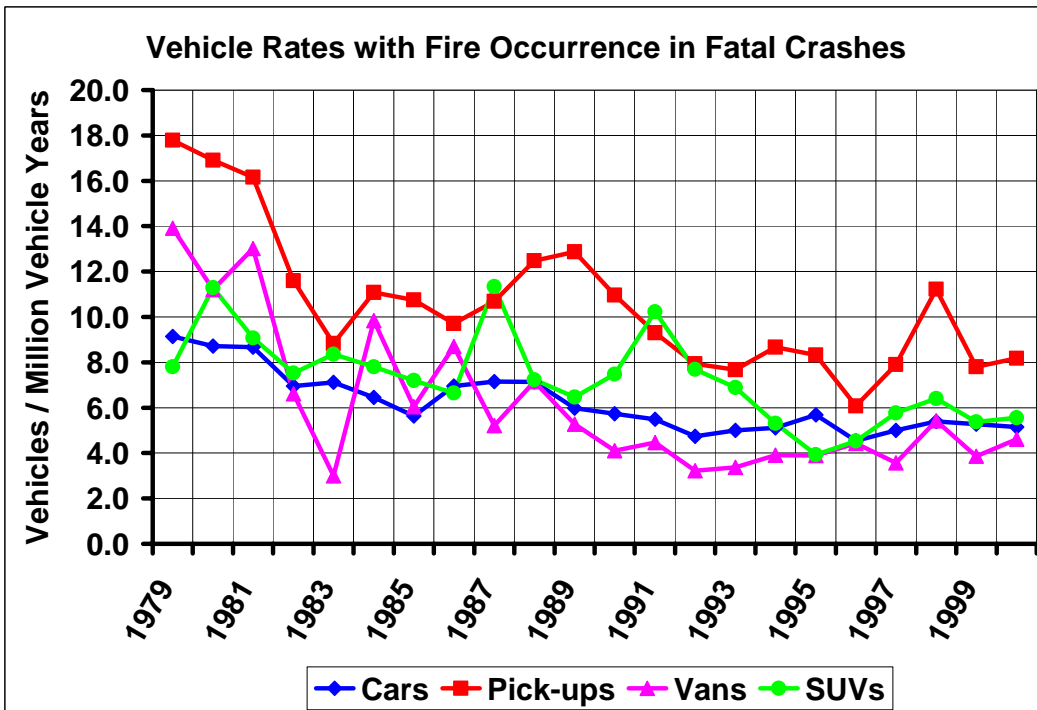


Figure 2. Rates per million vehicle registered years of vehicles involved in fatal crashes where a fire occurred in that particular vehicle (fatality did not necessarily occur in the vehicle with the fire). Data is from FARS 1979-2000, vehicle age is 0-4 years, and distributions are by vehicle type.

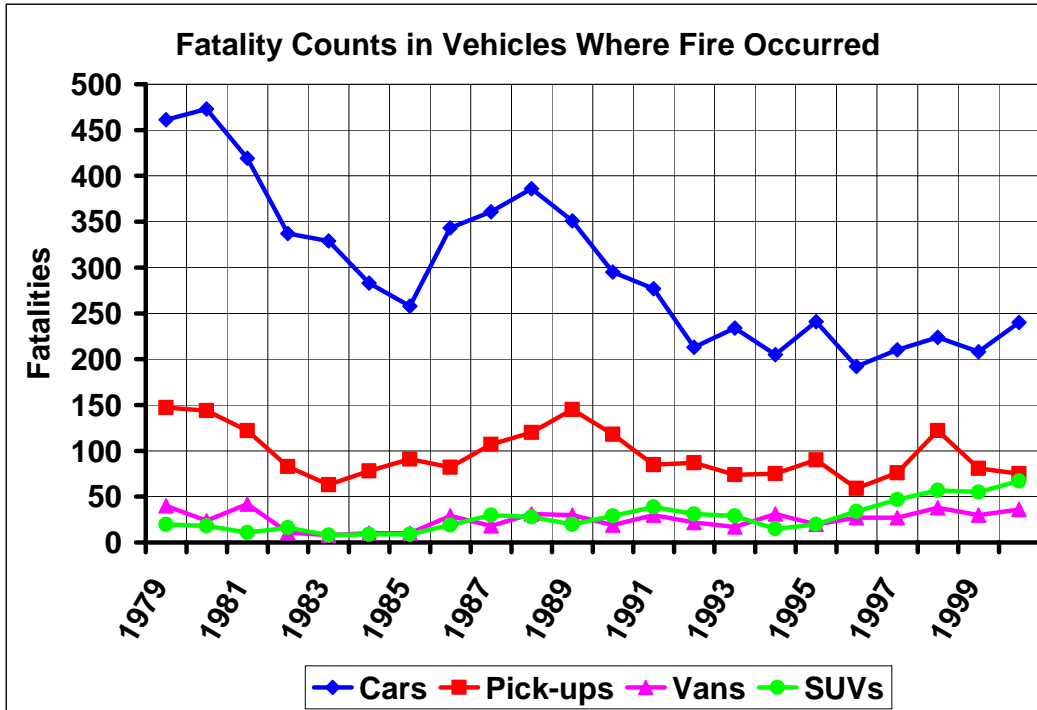


Figure 3. Fatality counts in vehicles where there was the occurrence of a fire/explosion (fatality is not necessarily attributed to the fire event). Data is from FARS 1979-2000, vehicle age is 0-4 years, and distributions are by vehicle type.

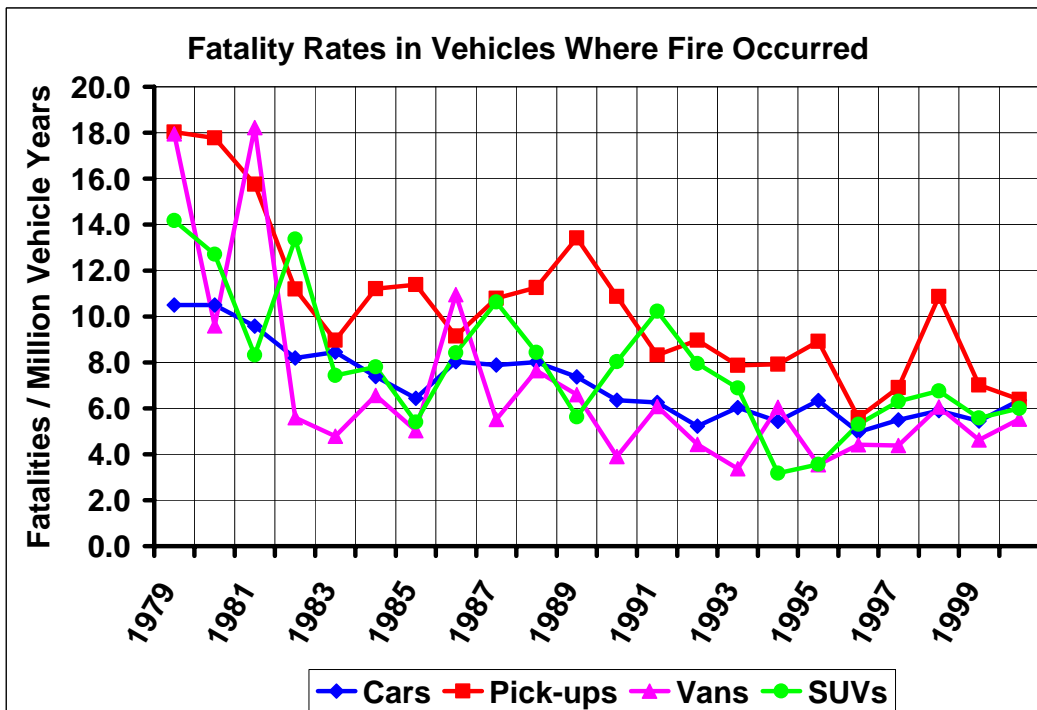


Figure 4. Fatality rates per million vehicle registered years in vehicles where there was the occurrence of a fire/explosion (fatality is not necessarily attributed to the fire event). Data is from FARS 1979-2000, vehicle age is 0-4 years, and distributions are by vehicle type.

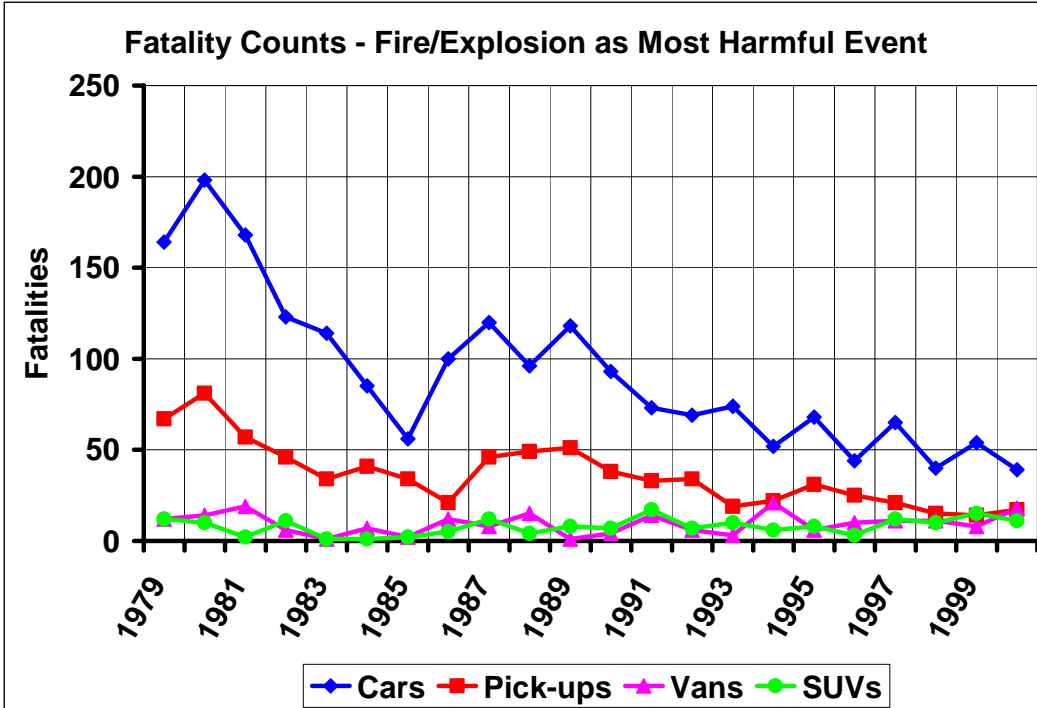


Figure 5. Fatality counts in vehicles where there was the occurrence of a fire/explosion and the fire event has been coded as the most harmful event (i.e. cause of death). Data is from FARS 1979-2000, vehicle age is 0-4 years, and distributions are by vehicle type.

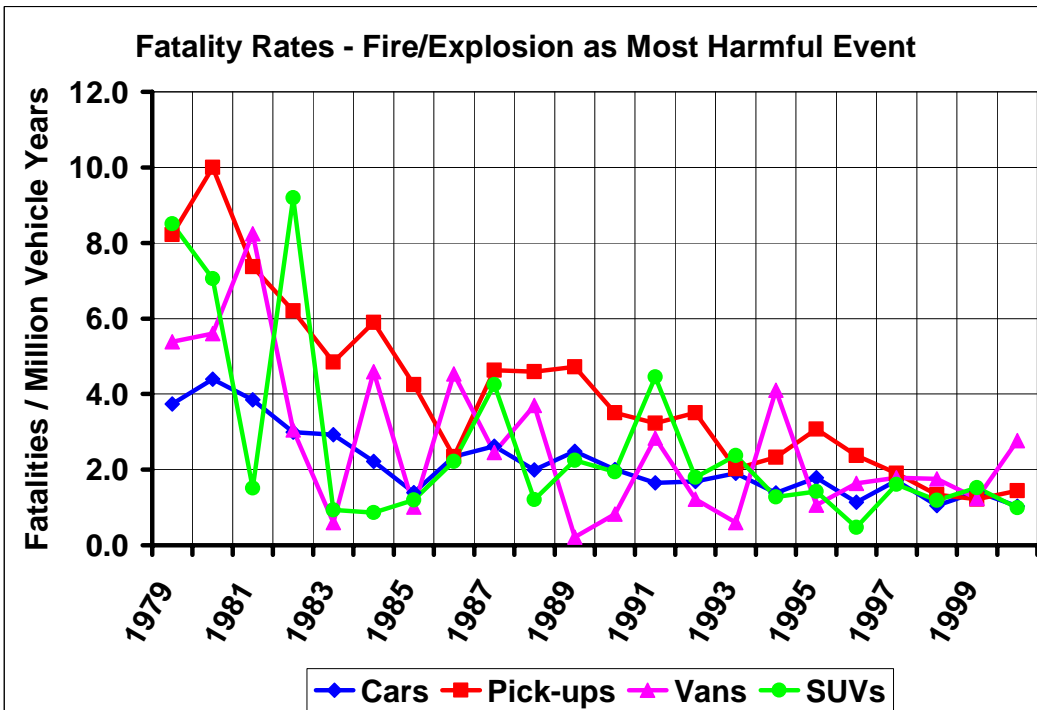


Figure 6. Fatality rates per million vehicle registered years in vehicles where there was the occurrence of a fire/explosion and the fire event has been coded as the most harmful event (i.e. cause of death). Data is from FARS 1979-2000, vehicle age is 0-4 years, and distributions are by vehicle type.

This study looks at vehicles of age 0-4 years; therefore, FARS year 2000 includes models years 1996-2000. A significant occurrence took place during model year 1976 with the introduction of the FMVSS 301 standard for fuel system integrity. Based on data in these figures, FARS year 1981 would be the first year with all vehicles FMVSS 301 compliant.

Figures 3 and 4 provide the fatality counts and rates for fatal crashes in which the fatality occurred in the vehicle where there was a fire. In these figures the fatality was not necessarily attributed to the fire event. Figures 5 and 6 relate the number and rate of fatalities to the fire event. In these figures, the fire event has been coded as the most harmful event, indicating it was the cause of the fatality. Often times it may be difficult to discern the cause of the fatality in these crashes (biomechanical trauma vs. fire trauma). This distinction was not investigated and the coding was taken directly from FARS. Previous studies have attempted to investigate the uncertainty and difficulty in coding fire as the most harmful event [Davies 2002].

It is positive to note that fire occurrence rates and fatality rates, including most harmful event rates, have declined since 1979 for all vehicle classes. With regard to fire occurrence counts and fatality counts, passenger cars and pick-up trucks have shown significant declines since 1979. Vans have remained relatively constant, while SUVs have shown a slight increase in recent years. The rise in SUVs is offset by the increased number of vehicle registrations over the same time period. SUV registrations have increased by 790% since 1979, and by over 300% since the early 1990's. Even with the increased exposure, rates have declined.

Passenger cars have shown the greatest decline in fire occurrence counts (207 fires - 51.6%), while pick-up trucks have the largest rate decline (9.62 fires/MVY). Pick-ups still maintain the highest rate for vehicle fires at 8.17 fires/MVY. In 2000, the fire rate for passenger cars was 5.14 fires/MVY, compared to 6.39 fires/MVY for light trucks. When looking at the overall decline in fire rates, cars have dropped by 43.7% and LTVs (pick-ups, vans, SUVs) by 59.7%. More importantly fatality rates by most harmful event have declined by 72.3% for cars and 79.7% for LTVs. Tables 1 and 2 display data from 1979 and 2000 for fire occurrence rates and fatality (most harmful event) rates respectively.

Table 1. Fire occurrence rates, vehicles age 0-4 in FARS

	Cars	Pick-ups	Vans	SUVs	All LTVs	All Vehicles
1979	9.13	17.79	13.91	7.79	15.86	10.56
2000	5.14	8.17	4.61	5.56	6.39	5.69
Change	4.00	9.62	9.30	2.23	9.47	4.87
Percent	43.7%	54.1%	66.9%	28.7%	59.7%	46.1%

Table 2. Fatality rates by most harmful event, vehicles age 0-4

	Cars	Pick-ups	Vans	SUVs	All LTVs	All Vehicles
1979	3.74	8.22	5.39	8.50	7.72	4.58
2000	1.03	1.45	2.77	0.99	1.56	1.27
Change	2.70	6.77	2.62	7.52	6.15	3.31
Percent	72.3%	82.4%	48.6%	88.4%	79.7%	72.4%

This FARS data is also being reviewed for such variables as crash mode (frontal, rear, rollover, etc.), impacting object, and more. Certain vehicle characteristics may reveal trends; however the relatively low number of fire events may prevent significant findings as the data is further categorized.

CASE REVIEWS OF VEHICLE FIRES

For the first phase of this study, the National Automotive Sampling System – Crashworthiness Data System (NASS/CDS) was used as the source of data in the analysis of detailed case studies. There have been two primary tasks completed to this stage. These include 1) the development of a NASS analysis tool for fire and fuel leakage cases, and 2) the application of this tool toward the study of NASS/CDS cases.

A crash query and case summary reporting tool is currently under development to help researchers review historical crash cases collected through NASS/CDS. The web based query page allows a user to select a specific subset of crashes from the database, based on desired crash conditions. It has been further enhanced to identify cases based on fire/fuel leakage variables.

The NASS/CDS tool performs a query based on a series of limiting conditions, and then returns two sets of information. First, data relating to the generated subset of crashes is available in tabular form. Since a large set of crash variables may be returned, a user is able to perform sorting and scanning on the data to look for trends and relationships between variables not evident during the initial query.

The second piece of information returned is a list of all cases that meet the query criteria. A user can select a case for further investigation. Following case selection, an automated summary sheet(s) is

generated with significant crash variables presented along with applicable pictures and scene diagram.

This query tool was used to identify and summarize 228 cases from 1997-2000 NASS/CDS in which there was a fire occurrence. These cases have been further analyzed to identify certain attributes of the crashes, which include:

- Investigate crash mode distribution in these cases (frontal, side, rear, rollover, etc.).
- Identify the ignition sources of the fires, along with fire location within the vehicle.
- Investigate accidents of similar severity and impact mode in which there was no fire, looking at injury distribution comparisons.

Although this study is ongoing, some initial results are available. It should be noted that NASS/CDS weighting factors were not used in this study due to the complexity and relative randomness of fire events. It was felt that the weighting factors could not be definitively applied to the fire events.

When looking at impact direction, the cases were divided into categories of impact that would be associated with the fire event. For example, if a frontal impact occurred with another vehicle followed by a side impact to a tree, and the tree impact was the source of a ruptured fuel tank, this would be classified as a side impact for this study. Based on this criterion, frontal impacts accounted for 117 cases (51.3%), side impacts 42 cases (18.4%), rear impacts 14 cases (6.1%), and rollovers 55 cases (24.1%). These results can be seen in Figure 7. It is interesting to note that rear impacts had the lowest frequency of fire events.

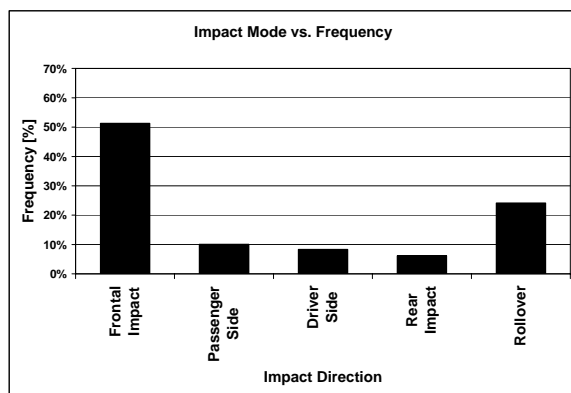


Figure 7. Distribution of fire events by impact direction.

Each impact mode is being further investigated to identify any possible trends. This includes impact mode in combination with impacting object and origin of the fire. Rollover events are being reviewed

to understand the various contributions of the role events. This includes roll severity (number of ¼ turns), roll direction, and fire origin relative to roll events.

The location and/or origin of the fire can provide useful information to researchers looking to further improve vehicle design and prevent fire events. The distribution of the fire origin within these NASS/CDS cases is shown in Figure 8. Of particular interest is that a large majority of fires (147 cases – 64.5%) initiated inside the engine compartment. In 26 cases (11.4%) it could be definitively determined that the fuel tank was the source of the fire. Often times it is difficult or impossible to determine the fire origin. This typically occurs in cases in which the vehicle was completely engulfed. There were 39 cases (17.1%) with unknown fire origins. This distribution is similar to previous studies and warrants further investigation into specific sources of fire initiation within the engine compartment.

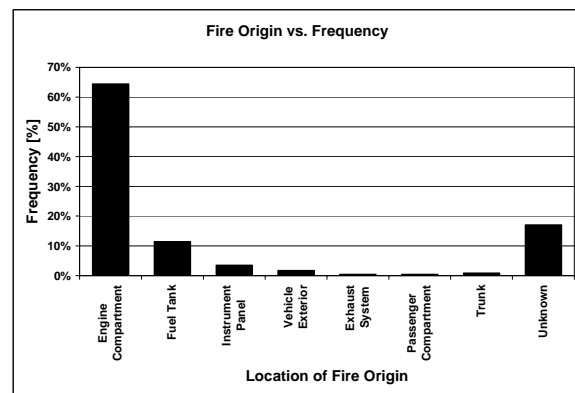


Figure 8. Distribution of fire origin/location.

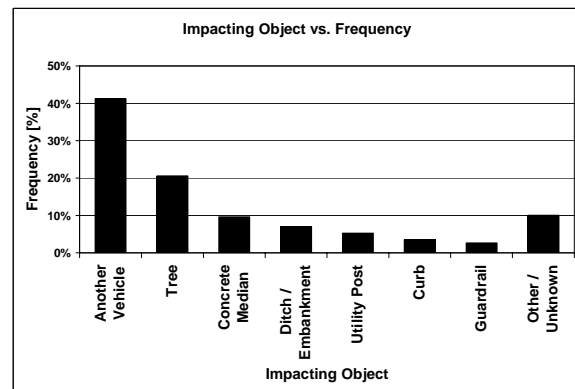


Figure 9. Distribution of fire events by impacting object.

This initial review of the data also identified the distribution of impacting objects for fire events (Figure 9). In 94 cases (41.2%) another vehicle was

the impacting object that was associated with the fire event. Although Figure 9 shows a more detailed breakdown of the impacting object, it can be seen that in 111 cases (48.7%) a fixed roadside object was the source of impact and the fire event. In a majority of these cases the fixed object is narrow and results in significant penetration at concentrated locations along the vehicle. Though further investigation is warranted and ongoing, impacts with fixed narrow objects account for a larger portion of the fuel tank related fires.

Of particular importance in any vehicle safety investigation is to study the relationships with occupant injury and fatality. While it is interesting to look at injury distributions within a particular type of event, it is also necessary to gauge the relative importance of the findings. For this study, it can be done by comparing all crash events with fire events. Injury distributions based on MAIS is shown in Figure 10. The data is displayed for all fire event cases along side all non-fire cases. It should be noted that the MAIS for the fire cases is associated with the fire event. For example, if the crash victim had an AIS 5 associated with steering wheel contact, and an AIS 2 associated with the fire event, the case is classified as MAIS 2 for this study. This attempts to normalize to a certain extent for the fire event, but it should be noted that it is often difficult to discern these injuries at higher severities.

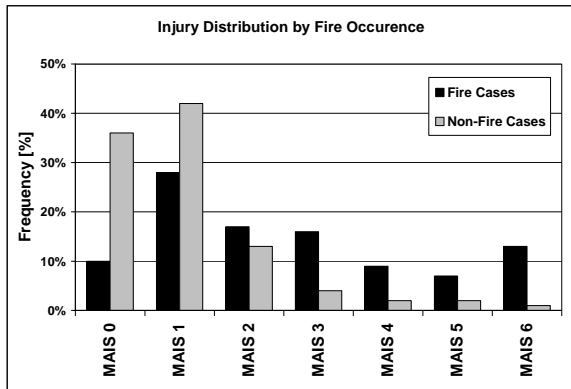


Figure 10. Injury distribution by MAIS for fire and non-fire cases.

Results show some interesting initial findings. Fire events tend to have a significantly greater percentage of MAIS 3+ associated injuries. While fire events are relatively infrequent, their occurrence tends to have greater associated harm. Further investigation into the injuries within each case is ongoing.

SURVEY OF STATE-OF-THE-ART IN FIRE SAFETY TECHNOLOGY

An investigation of the state-of-the-art in fuel systems has been undertaken with a focus on identifying fuel system fire safety technologies for preventing and/or mitigating post-crash fuel fires that may be in use today. An extensive survey will be conducted with in-vehicle evaluation and documentation of the various systems. Additionally, major fuel system components, such as the fuel tank itself, will be evaluated. The project is divided into two phases:

- Phase 1 defines the overall scope of the investigation and establishes procedures for carrying out the more specific review of individual systems. Included is a review of existing automotive fuel system standards.
- Phase 2 comprises the in-depth evaluation of the fuel systems from vehicles identified in Phase 1. The work performed under Phase 1 of the project is discussed herein.

Forty two different fuel system performance standards from world wide standards agencies and governing bodies were reviewed as part of the investigation into the state-of-the-art in fuel systems. These standards have been summarized and reported previously [Fournier 2001].

Various design strategies or technologies associated with the fuel system, which includes the evaporative emissions hardware, have been identified as potential countermeasures for preventing or mitigating the likelihood of post-crash vehicle fires. These strategies or technologies, which may already be employed in existing vehicles, include:

- **Filler check valve:** If the filler hose is torn from the tank a check valve located at the spout on the tank would prevent excessive fuel loss.
- **Shielding:** Shields may be used to increase the fuel system's resistance to damage resulting from direct contact and debris by providing an additional layer of protection.
- **Tank materials, thickness:** The choice of tank materials (plastic vs. metal) and its thickness will affect the resistance to punctures, tearing or bursting.
- **Multiple layered tanks:** Although principally used to address emission issues, multiple layered constructions may improve robustness.
- **Tank bladders:** Compliant and tear resistant bladders contained inside a tank prevent fuel

leaks if the rigid outer shell of the tank system is compromised.

- Tear away fuel line connections with check valves: These connections are designed to disengage and seal if excessive tension is applied to the fuel lines.
- Fire shields/blankets: Fire retardant shields, affixed to the hood fall into place to smother engine compartment fires.
- Anti-siphoning: The routing of fuel lines are such that if severed they would not continue to siphon fuel from the tank.
- EFI Fuel Pump shut off: The fuel pump would be deactivated if a crash is detected.
- Active fire suppression systems: Fire detectors would trigger the release of fire suppressant chemicals.
- Tank additives: Reticulate materials placed inside the tank to prevent explosions of the tank.
- Location, tank environment and routing of fill and delivery lines: Placement of fuel system components relative to potentially intrusive or aggressive components to minimize damage in the event of a collision.
- Slip-in-tube drive shaft: In a frontal collision of a rear wheel drive vehicle, the drive shaft would collapse along its length to minimize damage to a rear mounted tank.

The North American fleet comprises over three hundred makes and models of vehicles, not including variations within a model. The inspection of each one is beyond the current scope of the review which intends to gain a cross-section view of the best practices in fuel system fire safety design. A subset of these vehicles has been proposed and consists of a cross section of vehicle type (car, SUV, truck, etc.), manufacturer, price range, country of origin, etc. Also, vehicles with known technology implementations will be reviewed.

Information on each vehicle is collected and input into a Microsoft Access® database. This includes, but is not limited to:

- Tank shape and placement
- Presence of technologies listed previously
- Routing of fuel lines and components associated with the fuel delivery system
- Type and location of batteries and power sources
- Proximity of potentially “aggressive” structural components

In addition to visual inspections, vehicle brochures and user manuals will be reviewed, along with repair and maintenance manuals. Accompanying digital photos are also placed in the database.

A sample vehicle inspection has been completed as part of phase 1 of this study. Phase 2 – the inspection of 70 vehicles – is underway and all data will enter the public domain upon completion.

EVALUATION OF PLASTIC FUEL TANKS OF VARIOUS SHAPES

The purpose of this program is to conduct comparison evaluations of existing plastic fuel tanks to performance standards applied in Europe and also to standards applied to tanks for trucks in the US. The tests also examined degradation in service. Two ages of tanks were tested; 1) “conditioned” tanks, not older than four years, and 2) “new” tanks, from original equipment manufacturers (OEMs). The conditioned tanks were from vehicles that have been operated in a warm climate in the vicinity of San Antonio, Texas. The new tanks were purchased from the OEM supply and not from an after market supplier. The project evaluated three different tank design shapes.

The three tank design shapes are as follows: 1) a “pancake” tank typical of tanks in front wheel drive cars with a thin shape mounted to an underbody near the rear seat area and in front of the rear axle; 2) a “long” tank with a narrow shape mounted inside the frame rail and in front of the rear axle; and 3) a “square” tank mounted behind the rear axle. The three types of tanks are shown in Figures 11-13.

Three types of tests were conducted for new and conditioned tanks for each of the three tank shapes. The tests were: fire resistance, concentrated energy cold impact, and high energy impact.

The fire resistance tests were conducted in accordance with the European Standard for plastic fuel tanks, ECE R 34, Annex 5, Fire Resistance Section. This standard requires the plastic tank to withstand a pool fire for two minutes without leaking. In this test, the tank is mounted on the actual vehicle and filled with gasoline to 50% of capacity. For one minute, the vehicle and tank were subjected to the full intensity of a fuel-fed pool fire positioned directly beneath the tank. For the second minute, the intensity of the fire was mitigated by covering the fire pan with a screen. If the tank survives for two minutes it is said to “pass.”

In the research testing conducted under this project, a third condition was imposed. In this third condition, the screen was removed and the high intensity fire was continued until tank leakage occurred. Once



Figure 11. "Pancake" shaped tank pre-test.



Figure 14. "Pancake" tank after fire test.



Figure 12. "Long" shaped tank pre-test.



Figure 15. "Long" tank after fire test.



Figure 13. "Square" shaped tank pre-test.



Figure 16. "Square" tank after fire test.

leakage was observed, the fire was extinguished quickly by fire suppressants. The results reported in Table 3 shows the number of seconds after removal of the screen at 2 minutes until the tank leakage occurred

In these fire tests, all of the conditioned tanks were the original tanks installed on the 1998 model year

vehicles that were subjected to the burn tests. These conditioned tanks were tested before the "new" tanks were installed on the same vehicle. In all cases, the fire exposure caused some loss of body material from the vehicle. Consequently, added area for ventilation might exist in the second test. To reduce the effects of differences in ventilation, the vehicle with the "pancake" tank was rebuilt for the second test. The

other vehicles suffered less degradation and were not rebuilt. The second test of the “square” tank resulted in tank leakage at 101 seconds – 19 seconds short of the requirement. This difference could be explained by the increased ventilation permitted by the test buck.

Table 3. Number of Seconds After Removal of Fire Screen Until Tank Leakage Occurred

Tank Type	New	Conditioned
Pancake	90	90
Long	38	21
Square	-19	10

Other observations made from the tests included the location and size of the initial leak that occurred before the fire was extinguished. The two pancake tanks leaked at the same place – the bottom left rear corner. In both cases, the leaks were very small. The two square tanks both leaked in locations that were associated with loading by the mounting strap. Both tanks also leaked or were severely weakened at the front right top corner due to sagging of the tank. The rate of leakage from the square tank was greater than for the pancake tank. The two long tanks both leaked due to sagging of the front part of the tank that overhung the mounting straps. The leakage occurred at the front of the tank or at the straps. The rate of leakage was greater than the square tank. The post test deformation of the “pancake” tank, the “long” tank, and the “square” tank are shown in Figures 14 through 16.

Impact resistance was conducted on three new and three seasoned tanks. The impact tests were of two types. First tests were conducted in accordance with the European Standard for plastic fuel tanks, ECE R 34, Annex 5, Section 1 “Impact Resistance”. Second, tests were conducted in accordance with 49 CFR 393.67, “Liquid Fuel Tanks”.

For the ECE R 34 impact resistance test, the tanks are filled to rated capacity and chilled to -40 degrees C. At this temperature, they are impacted by a pyramid shaped 15 kg mass at an energy level of 30.1 Nm. In the research tests, tanks were impacted at the right front corner at energy levels ranging from 30.1 Nm to 43.6 Nm. No leakage occurred in any of the tests.

Federal Motor Carrier Safety Regulation CFR 393.67 “Liquid Fuel Tanks” requires an impact test condition that has not been applied to passenger vehicles. Section (e) (1) of the standard applies to side-mounted tanks and requires a drop test of the tank. In this test, the tank is filled with water to a weight

equal to the rated weight of fuel and dropped on its corner from a height of 30 ft. onto an unyielding surface. The standard limits the allowable leakage after the test to 1 oz per minute.

Table 4. Leakage rate in oz. per minute for Three Types of Tanks After 30 ft Drop Test per CFR 393.67 (e) (1)

Tank Type	New	Conditioned
Pancake	<1	<1
Long	<1	150
Square	<1	900

The results of the 30 ft drop tests are shown in Table 4. All of the new tanks and the seasoned pancake tank passed the test. However, both of the other seasoned tanks ruptured at the pinch-off separation. A typical breach of the tank is shown in Figure 17.



Figure 17. Seasoned “Long” Tank Post Drop Test

This limited research indicates that the tested tanks performed in a repeatable manner when subjected to ECE R 34, Annex 5, “Fire Resistance” Section. However, considerable difference in the margin for passing the test was present for the three tank types. In addition, the amount of leakage that occurred once the leak was initiated was vastly different. The behind the axle location of the “square” tank permitted the greatest amount of ventilation, and consequently may have been the most severe environment. The overhang of the long tank beyond the supporting straps appeared to be the most vulnerable feature of that tank shape. There was no identifiable difference between the performance of new and seasoned tanks in these tests.

All three tanks performed satisfactorily when subjected to the ECE R 34 Impact Resistance test, even when subjected to an impact with approximately

50% more energy than required by the test. No degradation was noted in the seasoned tanks.

All three new tanks performed satisfactorily when subjected to the Federal Motor Carrier Safety Regulation CFR 393.67 (e)(1) 30 ft. drop test. However, the seasoned “long” and “square” tanks leaked excessively after the drop. This result suggests some degradation of the resistance to severe impact with aging for these tanks.

DEVELOPMENT OF RECOMMENDED PRACTICE IN 42-VOLT APPLICATIONS

Major auto manufacturers are currently developing electrical systems that operate on 36-volt architectures, transitioning from the current 12-volt systems (14 volts when charging) typically used today. The 36 volt architecture charges at 42 volts, with possible voltage peaks as high as 58 volts. Current best practice and recommendations from ISO restrict the ability for human interface with voltages above 60 volts, thus the selection of the 36-volt architecture. Because the normal operating range is 42-volts, they are typically referred to as 42-volt systems.

There are several reasons why this transition is taking place. Power demands have been growing at about 6% per year for the last 15-20 years [SAE 2002, TOPTec 2002, Intertech 2002]. Modern cars consume between one and three kilowatts of power. They are near the limit of what can be done with the 12-volt architecture. This growth in power demand results from the expanding use of electronics in autos: radio and hi-fi systems, navigation systems, use of electrical outlets for plug-in computers, etc. In the future, there are many conventional systems that can be driven electronically. Electrically assisted power steering is now on the market. Electric brakes, electric rear wheel steering, electric suspension and stability control, electric drive for water and oil pumps, advanced automatic crash notification (ACN) systems, electric air conditioning and heating systems, and 110 volt AC outlets are all new applications which may be attractive after 42 volts becomes available. Some of these new components have fuel economy, emissions, and/or safety benefits.

Another major trend is toward “mild hybrids,” where the engine is shut off when stopped in traffic, and other systems, such as the air conditioning continue to operate. This technology is commonly referred to as an integrated starter generator and can provide approximately a 10% fuel economy improvement in city driving.

Even at 14-volts, there are fires caused by shorts and other malfunctions in the electrical systems. As was shown previously in the data analysis, more fires occur in frontal impacts, and initiate within the engine compartment. Since batteries are typically mounted in that region of the vehicle, and most of the under-hood fluids are flammable (including the engine coolant), there is reason to suspect that the battery may contribute to many under-hood fires. Batteries contain a great deal of energy (~ 3 million Joules for an 85 Ampere-hour battery). A short can dissipate hundreds of Watts, and can ignite surrounding flammable materials. A crushed battery can create either external or internal shorts and begin a heat release that can ignite the plastic battery case, and then spread to other under-hood materials.

If a circuit is broken with a 14-volt circuit, some sparking may occur, but not a sustained arc. With a 42-volt system there is likely to be a sustained arc when a circuit opens or there is a short to ground. This arc has tremendous power associated with it. It can easily produce 1000 Watts of power and release 1000 Joules per second. The temperature of the plasma can be 6000 C. This level of power can ignite most materials and can burn holes in sheet steel.

There is also another phenomenon called “Carbon Tracking” which can be present at 14 volts, but will be more common at 42 volts. It is caused by an electric field across an “insulator.” “Insulators” can conduct small amounts of electricity and gradually convert the hydrocarbons in the plastic to carbon - which is a good conductor. After considerable time (i.e. 10-15 years of a vehicle lifetime), this deposit of carbon can grow until it is capable of conducting a large amount of current. Shortly after the current builds up, the material will effectively short and cause an arc, and the material can flash into flame.

This process is accelerated by having conducting liquids or solids on the surface of the conductor. Oil, dirt, grime and moisture, which are readily available in the engine compartment, can get on the plastic electrical components and speed-up the process. Road salt (and battery acid released in a crash) are also conductors which can exacerbate the situation. 42-volt systems (with associated voltage margins) will be more susceptible to this phenomenon.

MVFRI is working with the USCAR 42-volt Working Group to fund a 42-volt research project at Underwriter’s Laboratories (UL). The purpose of this effort is to investigate Carbon Tracking phenomena with 25 different plastic samples that are

representative of materials used in connectors, terminal strips, and wire insulation. A 5% salt solution, typical of spray from salted roads in winter conditions, will be used to stress the material. One calibrated drop will fall every 30-seconds. After 50 drops (~25 minutes) the material is said to "pass." Some materials will be tested for 500 drops to validate that 50 drops is an acceptable stopping point.

The second effort under consideration will be to test a selection of materials to determine their flammability after being exposed to arcs likely to be created by 42-volt systems. These arcs are very high intensity and most materials will ignite if exposed long enough. The distinguishing factor is how much energy they can absorb before igniting. The number of materials is potentially much larger in number than for the carbon tracking testing. Any material that could be exposed to arcing needs to be tested - including some of the flammable under-hood fluids.

Results from these studies will be published at a later date and it is expected that these works may form the basis for recommended best practice and/or test standards associated with 42-volt systems.

CONCLUSIONS

For the year 2001, there were a total of 1,657 fatal crashes in which there was a fire. This is about 2.9% of all fatal crashes. Analysis of FARS data indicates that the fire rates in cars has dropped by 43.7% and LTVs (pick-ups, vans and SUVs) by 59.7% since the 1979. In 2000, the fire rate for passenger cars was 5.14 fires/million vehicle years, compared to 6.39 for light trucks.

For the years 1997-2000 the NASS/CDS contains 228 cases with fires. In these cases, frontal crashes accounted for 51.3% followed by rollover (24.1%) and side (18.4). Rear impacts accounted for the smallest fraction - 6.1%. The most frequent origin for the fire was the engine compartment, accounting for 64.5%. The fuel tank accounted for 11.4%. There were a relatively large number of unknown sources - 17.1%. The most frequent object impacted before the fire occurred was another vehicle (41.2%). However, a variety of roadside objects made up 48.7%. Narrow objects such as poles and trees contributed more than 25%.

Plastic tanks of three different shapes were evaluated to fire and impact testing as required by ECE R34, Annex 5 and US CFR 393.67 (e)(1). The ECE R34 fire test appeared to produce repeatable results and all tanks demonstrated the capability to withstand the

test. All tanks passed the ECE R34 impact test. The US CFR 393.67 (e)(1) requires the tank containing water equal to its rated weight of fuel to be dropped on its corner from a height of 30 ft. All new tanks passed the test. However, two of three tanks that had been in service for three years failed the test. In both cases the failure was pinch off separation, suggesting a possible deterioration of this junction with time.

Research is now underway to identify state-of-the-art technologies in present day motor vehicles. Other research is oriented to developing test methods to assure the fire safety of materials used in vehicles with 42-volt electrical systems. The results of this research will be made public as it progresses.

ACKNOWLEDGMENTS

The authors would like to recognize that funding for this research was provided by General Motors in accordance with the White, Monson and Cashiola vs. General Motors Settlement Agreement.

The authors would also like to recognize the contributions of several researchers and/or organizations that provided technical input to this paper. This includes: Friedman Research Corporation for the statistical data analysis, Biokinetics and Associates Ltd. for the survey of the state-of-the-art technology, Southwest Research Institute for the evaluation of plastic fuel tanks, and the George Washington University for the NASS/CDS case study reviews. Further details of research and progress associated with this work may be obtained at the following internet address: www.mvfri.org.

REFERENCES

- Davies, B. T., and Griffin, L. I., "A Clinical Evaluation of the Death Investigations for 206 Decedents Who Died in Passenger Vehicles that Experienced Post-Crash Fires," (January 2002) Docket # NHTSA-98-3588-170, Texas Transportation Institute.
- Fournier, E., and Keown, M. "Survey of the State-Of-The-Art in Fuel System Fire Safety - Phase I," (2001) Prepared for MVFRI by Biokinetics and Associates, Ltd.

"42 Volt Systems" *SAE TOPTEC* (April 2002) Troy, MI.

“42 Volt Technology 2002,” *SAE 2002 World Congress* (March 2002) SAE Publication SP-1661, Detroit, MI.

“Intertech Symposium on 42-volt systems,” (Sept. 2002) Cleveland, OH.

Judicial District Court “Agreement of Settlement, White, Monson and Cashiola vs. General Motors”, Number 42,865, DIV.”D”, 18th Judicial District Court, Parish of Iberville, Louisiana, June 27, 1996.

Malliaris, A.C., “Impact-Induced Car Fires: A Comprehensive Investigation,” (1991) *Journal of Accident Analysis and Prevention*, Vol. 23, No. 4, pp 257-273.

National Highway Traffic Safety Administration, “U.S. DoT/General Motors Settlement Agreement Status Report, Year 4”, NHTSA 2001.

Office of Defects Investigation, “Engineering Analysis Report and Initial Decision That The Subject Vehicles Contain A Safety Related Defect”, National Highway Traffic Safety Administration, Engineering Analysis EA92-041, NHTSA October 17, 1994.

“Traffic Safety Facts 2001,” (2002) National Center for Statistics and Analysis, NHTSA, 400 Seventh Street, S.W., Washington, D.C. 20590.