MVFRI RESEARCH SUMMARY

Kennerly H. Digges, Edmund Fournier

Survey of the State-Of-The-Art in Fuel System Fire Safety

Based on contract with:
Biokinetics and Associates, Ltd.

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 [Fournier 2005]. An extensive survey has been conducted with in-vehicle evaluation and documentation of the various systems. Additionally, major fuel system components, such as the fuel tank itself, have been evaluated. The project was divided into three phases:

- Phase 1 defined the overall scope of the investigation and established procedures for carrying out the more specific review of individual systems. Included was a review of existing automotive fuel system standards.
- Phase 2 comprised the in-depth inspection, documentation, and evaluation of the fuel systems in 74 model year 2002/03 vehicles.
- Phase 3 inspected an additional eight 2003vehicles that represented high sales models.

PHASE 1 - SURVEY OF STATE-OF-THE-ART IN FIRE SAFETY TECHNOLOGY

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 [Fournier 2002].

Various design strategies or technologies associated with the fuel system, which includes the evaporative emissions hardware, have been identified as potential countermeasures for 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 may 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 tank mounted near the drive shaft.

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 selected and consists of a cross section of vehicle types (car, SUV, truck, etc.), manufacturer, price range, country of origin, etc. Also, vehicles with known technology implementations have been reviewed.

Information on each vehicle was collected and input into a Microsoft Access© database [Fournier, March, 2004]. The items described and photographed include, but are 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 have been reviewed, along with repair and maintenance manuals. Accompanying digital photos have been placed in the database.

PHASE 2 – THE INSPECTION OF 74 VEHICLES AND SURVEY OF THE STATE-OF-THE-ART

Seventy four subject vehicles from the 2002 and 2003 model year North American fleet, representing various manufacturers, price ranges and classes were selected for inspection and investigation with respect to fuel systems fire safety technologies[Fournier 2003]. Included were nine of the vehicles tested in the development and evaluation of the proposed FMVSS 301 upgrade. The inspections comprised a visual examination of the fuel system components' installation, size and positioning measurements within the vehicle.

A subset of eighteen fuel systems from the seventy four subject vehicles was purchased and an additional component inspection was performed. Information pertaining to a tank's dimensions, capacity, construction and sub-components were recorded.

An electronic vehicle inspection database was compiled from the information and photographs gathered from the vehicle and the component inspections. In many instances, the use of tank safety features could not be ascertained with certainty due to the non disruptive nature of the vehicle inspections. Nevertheless, the fuel system inspection database may be used as a useful tool in comparing the safety features and tank installation features of the subject vehicles contained within.

Fuel system design considerations and technologies that may be beneficial in mitigating post crash vehicle fires were identified and reviewed. The design considerations discussed included:

- Structural crashworthiness of the vehicle frame
- Tank placement
- Fuel line routing/compliance
- Tank materials selection
- Fuel filler connections
- Electrical grounding
- Battery placement

The technologies that were reviewed included:

- Check valves for the tank filler tube

- Roll-over valves
- Shut-off mechanisms for electronic fuel pumps
- Returnless fuel systems that reduce the total length of fuel line that can potentially be damaged
- Crash sensing battery disconnects or cut-offs
- Collapsible drive shafts
- Self sealing breakaway connectors
- Fire retardant underhood blankets

More exotic fuel system safety technologies were also reviewed, many of which have been used in aviation and military applications. Some, however, have found use in special application automotive fuel tank systems whereas others may still be too costly or impractical for consumer vehicle use. These technologies include:

- Active fire suppression systems
- Tank filler material for explosion suppression
- Bladder tanks
- Self sealing tank systems
- Tank inerting systems

The total fire related safety for a given vehicle may involve a combination of various technologies in conjunction with crashworthiness design. Little field data exists to determine the effectiveness of these various fuel-system technologies on an individual basis, and it is difficult to assess crashworthiness design through visual inspection. Certain technology combinations may be more effective for a given vehicle, while others may add no benefit. While crashworthiness design is not reviewed here, the following sections describe the results of these inspections relative to fuel system design considerations.

VEHICLE INSPECTION FINDINGS - The following sections summarize some of the findings from the in- vehicle fuel system inspections and the detailed tank inspections as they relate to the tank design strategies and technologies described above.

<u>Tank Placement</u> - The placement of the fuel tank was categorized relative to the rear axle and the medial plane of the vehicle. If a physical axle was not present, the placement of the tank was taken relative to the axis joining the hubs of the rear wheels. The tank placement results, including the minimum and maximum clearances to the rear bumper, are summarized in Table 1.

Table 1 - Fore-aft placement of fuel tanks relative to the rear axle

Tank Fore-Aft Position	**No. of Tanks**	**Clearance from rear bumper (cm)**	
		min	**max**
Ahead of axle	64	86	195
Over axle	6	58	108
Behind axle	4	29	97

Table 2 - Lateral position of tanks forward of the rear axle

Tank Lateral Position	**No. of Tanks**	**Clearance from the sides of the vehicle (cm)**	
		min	**Max**
Left side	20	21	54
Mid-ship	40	17	67
Right side	3	30	39
Both sides	1	30	30

Figure 1 - Typical over the axle tank placement

For the 64 vehicles with their tank mounted ahead of the rear axle, the placement of the tank was further categorized relative to the medial plane of the vehicle as summarized in Table 2. Also included in Table 2 is the distance of the tank edge to the closest side of the vehicle. Referring to Table 2, there was one vehicle with a tank on both sides because of a dual fuel tank system. In general, a mid ship tank configuration was employed in a majority of passenger cars. The vehicles with their tank on either the left or right side, with the exception of two passenger cars, were either trucks or vans.

All six tanks that were situated over the axle, extend both forward and aft of the axle and were somewhat centered about the medial plane of the vehicle. Although extending towards the rear of the vehicle, the distance from the tank to the rear bumper was maintained between 91 cm to 108 cm, except for one vehicle that had a tank clearance distance of 58 cm from the rear bumper. A typical over the axle tank placement is shown in Figure 1.

Four of the 74 vehicles inspected had their tank situated behind the rear axle. However, of the four, one was installed vertically which allowed for a large clearance of 97 cm from the rear bumper. This clearance is similar to that of the tanks that were located above the axle and to some of the tanks installed ahead of the axle.

Fuel tanks from the other three vehicles essentially extended to the rear bumper. These vehicles maintained a tank distance between 29 cm and 31 cm from the rear bumper. The placement of the vertically mounted and a typical behind-the-rear-axle horizontal mount are shown in Figures 2 and 3.

Figure 2 - Behind-the-axle placement of the vertically mounted tank

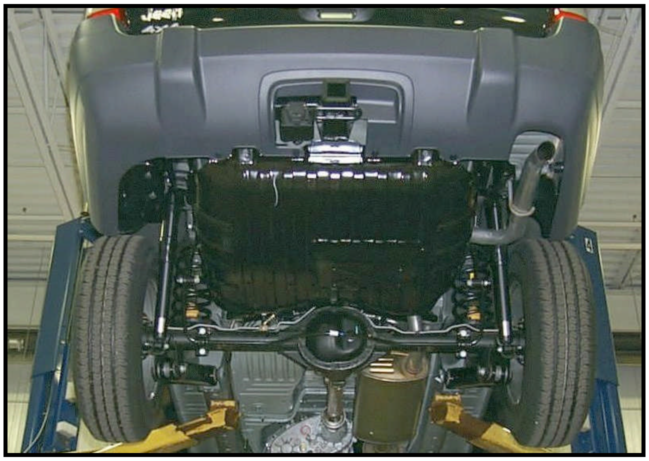

Figure 3 - Behind-the-axle placement of the horizontally mounted tank

Ground Clearance - Ground clearance of the fuel tank was measured from the lowest point of the tank. If a secondary shield was in place over the tank, the clearance was measured to the shield. The clearances are summarized in Table 3 for the different class of vehicles.

Table 3 - Range of ground clearance for different class of vehicles

Vehicle Type	Ground Clearance (cm)	
	Minimum	Maximum
Coupe/hatchback	14	32
Minivan	19	24
Pickup	28	41
Sedan	17	24
SUV	23	35
Van	34	40

Fuel Line Routing and Shielding - In all the vehicles the fuel lines were predominantly made of steel and were generally routed such that they derived protective benefits from a vehicle's structure. Typically, the fuel lines were routed along a frame rail or unibody frame rail. To varying extents, supplemental shielding of the lines afforded additional protection in 28 of the 74 vehicles inspected. An example of partial shielding is shown in Figure 4.

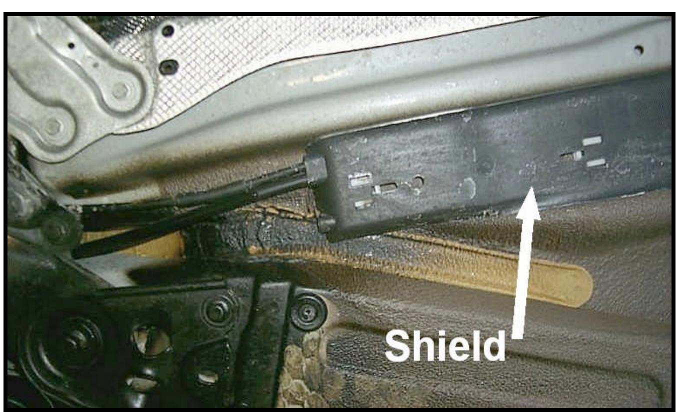

Figure 4 – Partial fuel line shielding

Tank Materials - Either plastic or steel are the materials of choice for the fabrication of fuel tanks. The incidence of their use in the 74 subject vehicles is presented in Table 4. Referring to Table 4, one vehicle's tank was classified as being fabricated with a combination of plastic and steel. The fuel tank is fabricated with a steel outer shell and an internal plastic tank as shown in the cutaway view of the tank in Figure 5.

Table 4 - Incidence of material used in the manufacture of fuel tanks

Tank Material	**No. of Vehicles**
Plastic	44
Steel	29
Combined	1

To better determine the ratio of plastic tanks to steel tanks, a quick survey of 64 additional vehicles displayed at a local auto show was conducted. Combining the results from the vehicle inspections and the auto show survey, but omitting tanks where the material could not be determined with certainty, it was found that 63% of the fuel tanks were fabricated from plastic and 37% were fabricated from steel.

Figure 5 – Cutaway view showing the plastic tank inside the outer steel shell

Tank Shielding - The use of tank shielding among the inspected vehicles is summarized in Table 5. Of the 13 vehicles that did not have shielding around the fuel tank, only one could conceivably be used for off-road driving and a skid plate package is available for that purpose. This optional package includes a tank shield.

Table 5 - Use of shielding on fuel tanks.

Tank Shielding	**No. of Vehicles**
Full coverage	13
Partial coverage	48
No coverage	13

Additional steel shielding was installed between the exhaust components and the tank in 67 vehicles where the exhaust system components were in close proximity to the fuel tank.

Fuel Pump Shut-off - Fuel pump shut-off usage could not be determined directly from the vehicle inspections, as these devices may be installed anywhere in a vehicle and are not apparent from a visual inspection alone. It was determined from OEM responses to the NPRM for the upgraded FMVSS 301 that most vehicles contain a fuel pump shut-off [NHTSA 2000]. Several manufacturers utilize an inertial shut-off device that responds to vehicle decelerations above that typically associated with normal stops.

Some manufacturers deactivate the fuel pump when the onboard computer senses a crash. The same sensors used to determine airbag deployment and battery disconnect are used for fuel pump shut-off. Other methods include an engine speed sensing device to shut off the fuel pump, and the use of engine rotation sensing devices.

Battery Disconnect - Two vehicles from the subject group use a battery disconnect. One of the Hybrid-electric vehicles uses the onboard computer to disconnect both the service battery and the high voltage battery for the electric traction motor.

Battery Placement - Typically, the 12 volt service battery in a vehicle is located under the hood, in the engine compartment of a vehicle. As shown in Table 6, this was the case in the vast majority of the vehicles inspected. Of the 64 batteries located under the hood, 14 were installed towards the rear of the engine compartment.

Table 6 - Battery location

Battery Location	No. of Vehicles
Under hood in the engine compartment	64
Batteries in the trunk	7
Other locations	3

The service batteries in three vehicles were installed in locations other than under the hood or in the trunk. The battery in one was located behind the left front bumper, with access to the battery gained through the wheel well. The other two vehicles' batteries were located inside the passenger compartment under the rear seat.

Three hybrid, gasoline/electric, vehicles were included in the vehicle inspections. In addition to the service battery, each of these vehicles employed an additional high voltage battery to power their auxiliary electric motor (280 volts from one battery and 144 volts from the other two). In all three instances this battery was located in the truck behind the rear seat and was electrically isolated from the remainder of the vehicle.

A recognized countermeasure for reducing electrical fires is an insulated cap placed over the positive battery terminal. Although not noted during the vehicle inspection, a summary of battery cap usage was determined from the database photographs and is presented in Table 7.

Table 7 - Summary of battery cap usage on the positive battery terminal

Insulated Cap Over Positive Battery Terminal	No. of Vehicles
Yes	56
No	8
Unknown	10

DETAILED TANK INSPECTIONS - A detailed inspection of 18 tank systems from the 74 inspected vehicles was carried out and a summary of the tank features that could not be fully ascertained during the vehicle inspections is presented below.

Corrosion Protection - The application of corrosion inhibitors in itself is not considered a fire safety feature, however, it may affect the integrity of the tank over time, which could affect fire safety in a collision. Of the 18 tanks inspected 8 were fabricated from steel. A summary of corrosion protection on these tanks is presented in Table 8.

Table 8 - Summary of application of corrosion resistance

Tank Surface	Outside	Inside
Painted	8	1
Galvanized	0	5
None	0	2

Filler Tube Connection - The filler tube connection to the tank was classified as positive, integral, or loose. In a positive connection the filler tube is mechanically fastened to the tank. An integral filler tube is molded simultaneous with the tank or welded on. With a loose connection, the filler is not mechanically fastened or integral with the tank. The filler tube itself was further classified as flexible or rigid. Examples of these connections are shown in Figure 6. The type of filler tube connection is summarized in Table 9 for the 18 tank inspections.

Table 9 - Summary of filler tube connection to the tank

Filler Tube Characteristics		Number of Tanks
Connection to Tank	Positive connection to tank	13
	Integral connection to tank	3
	Loose connection to tank	2
Rigidity of Filler	Rigid filler tube	5
	Flexible filler tube	13

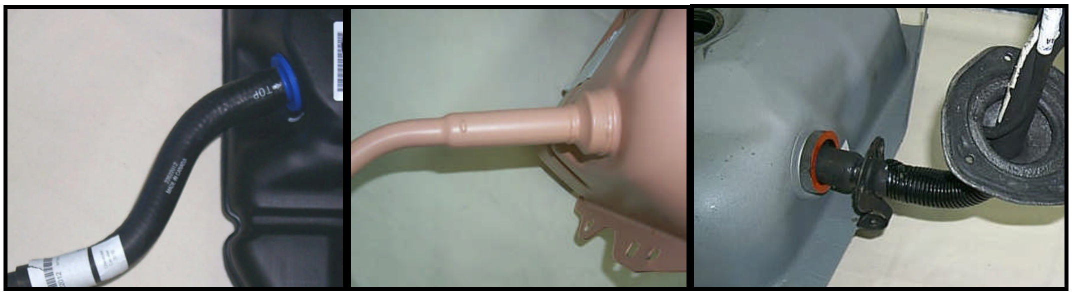

Figure 6 - Examples of (a) positive/flexible (b) integral/rigid and (c) loose/rigid filler tube connections to the fuel tank

Check Valves and Roll-over Valves - The presence of a filler neck check valve could not be determined during the vehicle inspections because disassembly of the tank system would have been required and the use of roll-over valves could not be determined with certainty because the top of an installed tank is not visible. The in-depth tank inspection provided the opportunity to dissemble and inspect individual tank components directly without hindrances. The incidence of use of these valves is presented in Table 10. Although it can not be positively confirmed without a detailed inspection of the tank components, it is believed that all vehicle tanks have a roll-over valve.

Table 10 - Presence of roll-over and check valves amongst the 18 detailed tank inspections

Tank Feature	Check Valve	Roll-over Valve
Yes	16	18
No	2	0

PHASE 3 – THE INSPECTION OF 8 VEHICLES AND DEVELOPMENT OF VEHICLE DATABASE

This final Phase conducted a preliminary analysis of the database of 73 vehicles to determine the percentage of sales that was represented [Fournier, Aug 2003; Fournier, May 2004]. Based on this analysis, eight additional high sales volume vehicles were added to the database. The follow-on research inspected an additional eight vehicles and provided a complete database of measurements, observations and photographs of eighty-two 2003 model year vehicles. The database may be accessed at: www.mvfri.org

The vehicles in the database are representative of the following percentages of vehicle sales volumes in MY 2003:

- **95% of pickups**
- **94% of minivans**
- **98% of full size vans**
- **72% of SUVs**
- **76% of passenger cars**

REFERENCES:

Fournier, E., and Keown, M., "Survey of the State-Of-The-Art in Fuel System Fire Safety – Phase I," Prepared for Motor Vehicle Fire Research Institute by Biokinetics and Associates, Ltd. Report R02-04, April 19, 2002. www.mvfri.org

Fournier, E., Bayne, T., and Kot, J., "Survey of the State-Of-The-Art in Fuel System Fire Safety – Phase II," Prepared for Motor Vehicle Fire Research Institute by Biokinetics and Associates, Ltd. , Report RO3-01, May 12, 2003. www.mvfri.org

Fournier, E., and Keown, M. "Preliminary Analysis of the Vehicle Fuel System Database," Prepared for Motor Vehicle Fire Research Institute by Biokinetics and Associates, Ltd. Report R03-16, August 18,2003. www.mvfri.org

Fournier, E., Bayne, T., and Kot, J., "Eighty-eight Vehicle MY 2002/03 Database for Fuel System Fire Safety," Prepared for Motor Vehicle Fire Research Institute by Biokinetics and Associates, Ltd., March 31, 2004. www.mvfri.org

Fournier, E., and Kot, J., "Summary Report: Expansion of the Vehicle Fuel System Database and Overview of Pickup Truck History", Prepared for Motor Vehicle Fire Research Institute by Biokinetics and Associates, Ltd. R04-02-V02, May 10, 2004. www.mvfri.org

Fournier, E., Kot, J., Sullivan, D., "Assessment of Fuel System Safety Technology Use in 2003 Model Year Vehicles", Society of Automotive Engineers (SAE) World Congress Paper 2005-01-1423, Detroit MI, April 2005. Available at www.sae.org