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Assessment of Fuel System Safety Technology Use in 2003 Model Year Vehicles

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ABSTRACT

In 1967, the National Highway Traffic Safety Administration (NHTSA) introduced the Federal Motor Vehicle Safety Standard (FMVSS) No. 301 "Fuel System Integrity", to ensure minimum fuel system integrity requirements were met. Recent studies of FARS and state data have shown a dramatic reduction of fire rates in motor vehicle crashes over the past 30 years. Design features and safety components are present in today's fleet that were not present when the standard was issued.

An investigation of the state-of-the-art in automotive fuel systems was conducted to examine the features of fuel systems in the 2003 fleet of vehicles. These features, in combination, have contributed to the reduction in fire rates. The investigation consisted primarily of an in-vehicle inspection of 89 fuel tank installations and a further investigation of fuel tank fire safety technologies.

Fuel tank design features and the presence of system components that would aid in the prevention or mitigation of post crash fires were documented and entered into a database. Additional information relating to the fuel line routing, the use of fire safety technologies and the proximity of potentially aggressive components were also documented.

It is estimated that 80% of vehicles sold in 2003 are represented in the database when sister models and corporate cousins are considered.

A summary of some of the fuel safety features and the frequency of their presence is presented in the paper.

INTRODUCTION

Post crash vehicle fires result from the ignition of flammable materials or fuels that may be expelled during and after a collision. Gasoline, the most volatile of such fuels, may leak directly from a damaged fuel tank or from torn or severed fuel lines. In the presence of an ignition source, this poses the greatest risk of rapid conflagration. The crash environment presents several possible ignition sources, including:

- Hot vehicle components such as the exhaust system.
- Sparks generated from steel vehicle components scraping the ground.
- Sparks generated from metal to metal contact with an opposing vehicle.
- Heat and sparks generated by the crush of a vehicle's structure.
- Electrical arcing from broken or exposed wires.
- Electrical heat generated from short circuits of primary and secondary wiring.
- Electrical heat generated from internal shorting of battery plates.

The design criteria for a fuel system should include considerations for reducing the possibility of post crash vehicle fires. Features such as structural crashworthiness design, material selection, fuel tank location in the vehicle, and add-on technologies must all be considered.

In 1967, the National Highway Traffic Safety Administration (NHTSA) introduced the Federal Motor Vehicle Safety Standard (FMVSS) No. 301 "Fuel System Integrity". The intent of the standard was to reduce the incidence of deaths and injuries resulting from post crash vehicle fires by ensuring that the fuel systems in new vehicles met minimum crash integrity requirements.

Presumably the fuel systems in the 2003 North American fleet of vehicles all meet the FMVSS 301 requirement. Furthermore, the tank systems of many of these vehicles employ counter measures that would aid in the prevention or mitigation of post crash vehicle fires under other varied crash configurations not specifically addressed by the standard.

An investigation of the state-of-the-art in automotive fuel systems was conducted to establish the best practices in fuel system design and implementation in the current North American fleet of vehicles. The investigation consisted primarily of an in-vehicle inspection of 89 fuel tank systems and a complete tear down and inspection of 20 fuel tanks and their associated components. Included was a review of available fuel containment and fire suppression technologies. Some of these technologies are not commonly employed in consumer automobiles but are typically limited to aviation or military applications due to cost or complexity restrictions. Nevertheless, these are briefly discussed as they do represent the state-of-the-art in fuel system fire safety technology.

VEHICLE SELECTION

The investigation of the state of–the art in fuel systems included the inspection of 89 vehicles from the over 300 makes and models of vehicles represented in the 2003 North American fleet [Fournier at al, 2003 and May 2004]. The selected vehicles were intended to highlight the best practices employed in current fuel system design.

Initially, vehicles known or suspected to incorporate fire preventative technologies or design strategies were included in the review. Vehicles that had been involved in fuel system fire safety related recalls were also included, as the improvements to their fuel systems would highlight considerations for a fuel system's design. The list was rounded out with vehicles from various manufacturers, price ranges and classes, such as SUVs, pickup trucks, vans and passenger cars.

A summary of the manufacturers represented in the database is presented in Table 1.

Table 1: Number of inspected vehicles by manufacturer.

Manufacturer	No. of vehicles
General Motors	18
Ford	12
Chrysler	12
Toyota	11
Honda/Acura	9
Nissan/Infiniti	6
Mazda	3
KIA	3
BMW	3
Volvo	3
Audi	2
Hyundai	2
VW	2
Mercedes	2
Subaru	1

As indicated, 89 vehicles were inspected, however, if sister models and corporate cousins are included the number of vehicles represented by the database becomes 129. This represents 79% of North American vehicles sales for 2003. Estimates of the 2003 sales numbers were obtained from the Automotive News Datacenter [Automotive News] and are presented in Table 2.

Table 2: Estimates of 2003 vehicles sales.

Year	2003
Total sales of database vehicles including clones	13,092,313
Total US car sales	7,809,834
Total US light truck sales	8,865,894
TOTAL US Sales	16,675,728
Percentage of total sales represented by database vehicles	79%

The number of vehicles from different vehicles classes is presented in Table 3 with their corresponding sales estimates shown in Table 4.

Table 3: Number of vehicles per vehicle class.

Vehicle Type	No. of vehicles represented		
	Inspected	Sisters / Cousins	Total
Sedan/Coupe/ Wagon	51	22	73
Sport Utility	20	10	30
Pickup Truck	8	3	11
Mini-van	7	4	11
Full-size van	3	1	4

Table 4: Sales estimates for each vehicle class represented.

Vehicle Type	Sales of database vehicles vehicle class	
	2003	% of total sales*
Sedan/Coupe/ Wagon	5,924,753	76
Sport Utility	3,001,954	69
Pickup Truck	2,988,582	96
Mini-van	977,719	96
Full-size van	283,058	76

* The percentage of total sales is calculated on sales quantities for the given vehicle type.

VEHICLE FUEL SYSTEM INSPECTION PROCEDURE

The vehicle fuel systems were inspected in situ and for a subset of 20 vehicles the fuel system components were purchased and evaluated in more detail.

VEHICLE INSPECTIONS

The 89 subject vehicles included in the review were made available for inspection through the cooperation of many automotive dealerships that not only provided the vehicles for the inspections but also the use of a vehicle hoist.

The fuel system inspections comprised of observations regarding the installation, and size and positioning measurements of the various fuel system components within the vehicle. The vehicles were not altered or disassembled in any way to obtain a better view or to determine the use of a particular fire safety technology that may have been occluded. In particular this limited the view of the components and connections on the top of the tank. This limitation, however, was partly overcome by purchasing 20 fuel systems and inspecting the components directly.

Generally, the information gained through the vehicle inspections included:

- The placement of the tank relative to the extents of the vehicle.
- The presence of fire safety related technologies.
- The routing of fuel lines.
- The proximity of aggressive components which could potentially be damaging to the fuel system in a collision.

Additional information pertaining to the vehicles was obtained from service technicians, parts lists and shop manuals. The parts lists and shop manuals were useful in determining the presence of components that may not have been visible during the inspection.

Data collection from the vehicle inspections followed a predefined checklist that included information regarding:

- The vehicle in general.
- The battery placement.
- The fuel system, which comprises the fuel tank, fuel lines, fuel filler, canister and the fuel filter.
- Specific fire safety related features.

If a specific feature was not apparent or could not be determined it was classified as unknown.

The data recorded and the many vehicle and tank photographs were transcribed into an electronically accessible database created using Microsoft Access®.

TANK DESIGN CONSIDERATIONS

The review of the tank installations focused on design features that were considered to have the greatest influence in optimizing a fuel system's crashworthiness. The vehicle inspection check list attempted to identify and where possible quantify these features. The design features are discussed briefly in the following sections.

STRUCTURAL CRASHWORTHINESS DESIGN

The structural design of a vehicle is undoubtedly very important in preventing or mitigating fuel system damage and possibly loss of integrity in a crash. An otherwise well designed tank system may exhibit poor crashworthiness if the vehicle structure does not provide adequate protection from crash loads or from impingement into the tank space. Conversely, a less robust tank design may perform favorably if afforded sufficient protection by the vehicle structure. The vehicle inspections alone, however, are insufficient to ascertain the performance of a vehicle's structural design. Structural integrity in a crash environment can only be evaluated with integral knowledge of the structural design, through crash testing or analysis of field data. Consequently, the implementation or lack thereof of other tank technologies or design considerations is in itself insufficient to evaluate the crashworthiness of a tank/vehicle system.

TANK PLACEMENT

In an ideal installation the fuel tank would be situated where the damage sustained would be minimal under various crash configurations that include frontal, rear and lateral collisions. Therefore, the tank should be placed in a location best protected by surrounding structures designed to mitigate crash forces. The immediate area around the tank should also be free of components that may be intrusive to the tank, such as hard edges or protruding bolts. If displaced sufficiently in a crash, these items could pierce or tear open the tank.

The structure of the vehicle can also be used to enhance the protection afforded the tank by virtue of its location in the vehicle. For example, the forward region proximal to the rear axle may have added protection against lateral intrusion offered by the rigid structure of the axle. Similarly, in pickup trucks the substantial frame rails might effectively improve fuel tank protection.

Reducing wear and tear on the tank from such road hazards as dirt, rocks and other road debris that may be encountered in daily or specialized driving conditions should also be considered. Depending on the use of the vehicle, the tank's ground clearance can be optimized. Technologies such as debris shields can be incorporated to protect under certain conditions. These are commonly incorporated into off-road and utility vehicles.

FUEL LINE ROUTING

The fuel lines from the tank to the engine should be routed to obtain the maximum amount of protection from damage in a crash. This may be accomplished by routing the lines along structural components or providing additional shielding to protect against potentially aggressive edges on an impacting vehicle or intruding structures. The routing of the fuel lines should avoid the proximity of the exhaust components or hot engine components. If the lines are severed in a crash it is best to keep any possible leaking fuel from coming into contact with a hot component. Additionally, a design consideration may be to add compliance in the fuel lines to allow for elongation of the routing path as a result of vehicle crush and deformations.

MATERIALS SELECTION

The choice of fuel tank materials can affect the vapor emissions, the crashworthiness, the manufacturability and the long term durability of a tank system. The selection of tank materials should consider:

- Minimizing evaporative emissions. Steel is inherently impermeable to fuel vapor and new plastic formulations have been developed that reduce the vapor permeation in plastic tanks.
- Resistance to damage. Steel and plastic have different material properties and thus will have different resistance to damage. The choice of materials must consider the environment to which the tank may be exposed.
- Manufacturing methods. Plastics allow for complex geometries to be molded. Newer, highly formable steels and steel manufacturing methods, however, do allow for forming steel into more complex shapes than previously possible.
- Corrosion resistance. Plastic tanks are corrosion resistant and, therefore, should not suffer degradation of their structural integrity. However, results of limited tests sponsored by the Motor Vehicle Fire Research Institute suggest some degradation of aged plastic tanks may occur particularly at the pinch off [Digges at al]. According to the Strategic Alliance for Steel Fuel Tanks, properly treated steel tanks can effectively resist corrosion for over 15 years.

The points listed above impartially highlight the need to carefully evaluate the operating environment and to select a material that is most appropriate for a specific tank design or application.

FILLER CONNECTION

Even though a tank itself may be well removed from direct impact in a collision, the filler tube is susceptible to damage and/or possible displacement from its design position. If the filler tube is rigidly attached to the tank the crash forces can be transmitted through the tube, to the tank, potentially damaging the tank and causing fuel leakage. It is, therefore, prudent to ensure a compliant connection of the filler tube to the tank. In an extreme case where the filler tube is severed, provisions, such as a check valve, should be incorporated in the design to prevent fuel loss.

GROUNDING

Under the right circumstances of humidity and fuel vapor concentration, a static electricity discharge between two objects of different electrical potential can ignite fuel vapors. The individual components of a fuel system should be commonly grounded to avoid the possibility of an electrostatic discharge (ESD) occurring, which may not be associated with a crash event.

SERVICE BATTERY

Following a collision, electrical arcing from damaged wiring is a potential source of ignition for spilled fuel. This can be prevented with a crash activated battery disconnect/cut-off that disconnects current to the vehicle's electrical systems.

Additionally, the battery should be positioned to avoid damage that may result in electrical shorting within the battery itself, or of the positive battery terminal, which can ignite the battery. An insulated cap placed over the positive battery terminal may minimize the possibility of electrical arcing with displaced metal components.

TANK FIRE SAFETY TECHNOLOGIES

A review of fuel system fire safety technologies with applications in the automotive, aviation and military industries was undertaken and is summarized in the following sections. In principle, all these technologies can be incorporated into a fuel system's design to mitigate post crash fuel fires. However, the implementation of some of the technologies may be impractical due to prohibitive costs, reliability or suitability for a given application. Neither the design intent nor the described efficacy of the technologies discussed in this section has been supported with field data or independent testing.

The presence of these technologies was recorded during the vehicle inspections

FUEL FILLER CHECK VALVES

The function of a fuel filler check valve is to prevent fuel spillage if the fuel cap or the filler tube is damaged in a crash. It is designed to allow fuel flow in one direction and to restrict flow in the opposite direction. It is normally closed but will open under fuel pressure to allow tank filling to occur. Ideally, the valve would be installed as close as possible to or in the tank to minimize the potential of the valve itself being damaged.

ROLL-OVER VALVES

A roll-over valve prevents fuel from entering a tank's vent lines if a vehicle is overturned during a collision. The vents allow for pressure balancing either to prevent suction in the ullage when fuel is consumed or conversely to prevent excessive vapor pressure build-up. The valves which are gravity actuated are orientation sensitive and must exceed a minimum rotation from their upright orientation before the valves engage. Springs or shifting ballast are two means used to increase the sensitivity of the valves to inversion.

FUEL PUMP SHUT-OFF

A fuel pump shut-off disables the fuel pump following a collision and prevents it from continuing to function and expelling fuel from a potentially severed fuel line.

The fuel pump shut-off switch can be either inertially or electronically activated. With an inertial type switch, a crash pulse causes a mass within the switch to shift, breaking the electrical connection to the fuel pump. A cut-away view of an inertial switch, produced by First Technology is shown in Figure 1. Such a switch is used in the Ford Focus and other Ford vehicles.

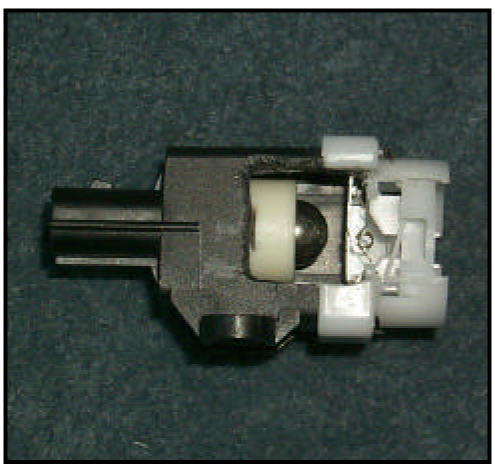

Figure 1: Example of an inertially activated fuel pump shut-off switch.

With electronically activated systems the vehicle's onboard computer uses crash sensors or engine rotation sensors to monitor for a crash event. If a crash is detected power to the fuel pump is disconnected.

RETURNLESS FUEL SYSTEMS

Conventional fuel pump systems provide more fuel than the engine requires resulting in a constant circulation of fuel to the engine, through the fuel delivery line, and returning back into the fuel tank via a return fuel line. Electronic returnless fuel system (ERFS) have eliminated the need for the return line by using a pressure regulator, typically integrated with the pump assembly, that only produces the quantity of fuel required by the engine.

The elimination of the return line prevents hot fuel vapors from returning to the fuel tank resulting in reduced evaporative emissions and the added safety benefit of fewer fuel lines that can potentially be severed.

POSITIVE BATTERY TERMINAL COVER

A recognized countermeasure for reducing electrical fires is an insulated cap placed over the positive battery terminal [Johnson 1975]. Such a cover will mitigate the possibility of electrical arcing between the positive battery terminal and grounded vehicle components that may come into close proximity due to vehicle crush following a crash.

BATTERY DISCONNECT/CUT-OFF

In a sufficiently severe collision a battery disconnect or cut-off disconnects power to the vehicle's electrical systems by severing the electrical connection to the positive battery terminal. This is done to minimize the chances of electrical shorts and arcing from damaged wiring which can act as an ignition source for spilled fuel. Power to essential vehicle functions, such as the door locks and electric window mechanisms, is maintained.

Two mechanisms for disconnecting the battery were identified. The first employed a pyrotechnic charge to disconnect power and the second disconnected the power electronically. With both systems the power from the battery is interrupted within 3 ms of a crash being detected.

An example of a pyrotechnic battery disconnect from a BMW, with the integral squib on battery post end of the cable, is shown in cutaway view in Figure 2 before and after activation.

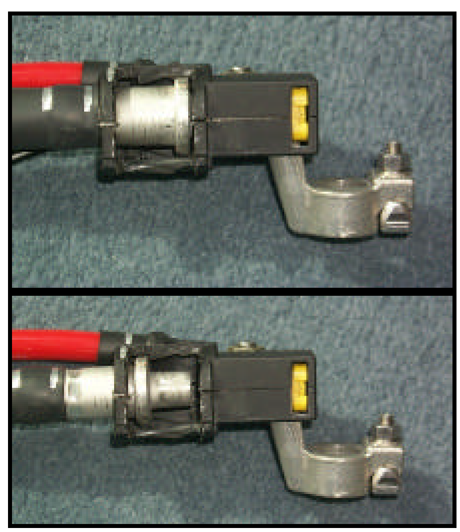

Figure 2: Cut-away view of a pyrotechnic battery disconnect.

COLLAPSIBLE DRIVE SHAFT

Although not a component of the fuel system, the drive shaft in rear wheel drive vehicles may pose a potential threat to the crashworthiness of a fuel tank. A collapsible drive shaft would absorb energy from a frontal collision by incorporating compliance in the shaft design that would aid in mitigating its possibility of buckling, thereby reducing the possible undesirable contact with the fuel tank.

SELF-SEALING BREAKAWAY CONNECTORS

Self-sealing breakaway connectors on the fuel lines are used in the auto racing industry. They are designed to disengage when a predefined tensile load limit is exceeded. Once disconnected, the resulting free ends of tubing are instantly sealed to prevent fluid loss. If a tank experiences excessive displacement during a collision or if its mounting hardware fails and the tank is ejected, the self-sealing connectors would help to prevent the fuel lines from severing and causing excessive fuel spillage.

ACTIVE FIRE SUPPRESSANT SYSTEMS

Active fire suppressant systems are widely used in commercial, marine, military and aircraft applications. Upon sensing the presence of a fire, an active fire suppressant system, installed in a vehicle, would disburse a fire suppressant agent to extinguish the fire. There are no known automotive applications of such a system although research has been conducted into their use under simulated engine compartment and under body fire scenarios.

PASSIVE FIRE SUPPRESSANT SYSTEMS

<u>Fire Retardant Blankets</u>

The presence of under hood insulation was recorded during the vehicle inspections. Toyota and Ford dealerships claimed that the mounting lugs that affix the insulation to the underside of the Sienna and F150 hoods would melt from the heat of an engine compartment fire causing the insulation blanket to drop down and smother the fire. The fire retarding qualities of the insulation could not be ascertained through visual inspection alone.

<u>Powder Panel</u>

Powder panels were originally developed by the military, both for aircraft and ground vehicles, to prevent fuel fires following a ballistic strike to a fuel tank. They are constructed of hollow panels filled with a dry chemical fire suppressant and then sealed. When the panels are compromised, a cloud of fire suppressant powder is emitted to extinguish or prevent ignition of spilled fuel. Following the initial release of the fire suppressant, a cloud of suppressant remains for an extended period and may prevent delayed ignition.

<u>Explosion Suppressant Tank Fillers</u>

Explosion suppressant arresting foam (ESAF) was developed for use in military aircraft and auto racing. If a tank is damaged in a crash the ESAF works to prevent or mitigate the chance of an ensuing fuel fire by confining the ignition of fuel vapor to the immediate area of the ignition source. The ESAF is manufactured from reticulated polyurethane foam whose structure is 98% void. A similar technology uses matted aluminum mesh instead of foam.

<u>Tank Bladder</u>

A bladder tank consists of a tough rubberized membrane that by virtue of its compliance is resistant to impact. Used in auto racing, the bladder is contained within a metal outer container which affords additional protection from impact.

<u>Self Sealing Fuel Tank</u>

The primary use of self sealing technologies is to prevent fuel loss from small arms ballistic impact. Typical applications of this technology include military vehicles and dignitary limousines. There are variations to the construction methods used to fabricate a self sealing tank. Each method typically encapsulates a tank with multi-layers of material that are vulcanized to the tank's outer surface. Rubberized inside and outside layers surround a fuel activated sealant layer. If the fuel cell is penetrated two sealing mechanisms occur. Firstly, the outer and inner rubber layers quickly close around the hole to minimize fuel leakage. Secondly, the fuel that leaks through the hole in the inner layer reacts with the sealant causing it to swell several times it normal size providing an effective means of stopping further fuel leakage.

<u>Inerting Systems</u>

The aircraft industry, primarily with regards to military applications, has adopted an onboard system that reduces the concentration of oxygen that, when mixed with fuel vapors, results in a highly flammable mixture in the tank ullage. On-board inert gas generating system (OBIGGS) draw in ambient air and filter out approximately 98% of the oxygen molecules and the remaining nitrogen enriched air is pumped into the ullage of the fuel tank preventing volatile oxygen/vapor concentrations.

FINDINGS: VEHICLE INSPECTION

The following tables (Table 5 to Table 8) are examples of the use of the database to ascertain the prevalence of some of the specific design features and technologies discussed above [Fournier, September 2004].

Table 5: Fore-aft placement of the fuel tank relative to the rear axle.

Tank Fore-aft Position	No. of vehicles represented by database			Clearance from Bumper (cm)		Sales	
	Inspected	Sister / Cousins	Total	Min	Max	2003	% of total sales
Ahead of Axle	77	33	110	81	195	11,538,664	69
Behind Axle	6	4	10	29	98	816,662	5
Over Axle	7	3	10	58	108	820,740	5

Table 6: Incidence of material used in the manufacture of fuel tanks.

Tank Material	No. of vehicles represented by database			Sales	
	Inspected	Sister / Cousins	Total	2003	% of total sales
Steel	35	8	43	4,370,664	26
Plastic	54	32	86	8,780,775	53
Steel and Plastic	1	0	1	24,627	0

Table 7: Use of tank shielding.

Tank Shielding Coverage	No. of vehicles represented by database			Sales	
	Inspected	Sister / Cousins	Total	2003	% of total sales
Full	18	3	19	2,562,097	15
Partial	58	30	88	9,184,866	55
None	16	7	23	1,429,103	9

Table 8: Incidence of battery cap usage on positive battery terminal.

Cap on Positive Battery Terminal	No. of vehicles represented by database			Sales	
	Inspected	Sister / Cousins	Total	2003	% of total sales
Yes	82	39	118	12,264,731	74
No	7	4	11	827,582	5

TANK COMPONENT INSPECTION

The complete fuel systems from 20 of the inspected vehicles were purchased and their resistance to leakage was evaluated [Fournier et al, July 2004]. Additional inspections and measurement that could not be performed in situ without disassembly of the tank system were also performed. Information pertaining to a fuel tank's dimensions, capacity, construction and components were recorded and included in the electronic database.

TANK LEAK TESTS

The leak 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 filled with water instead of gasoline or Stoddard which is typically used in automotive testing. It was understood that the properties of these liquids are different, however, it was believed that any leakage encountered solely because of the difference in material properties would be negligible. Nevertheless, liquid soap was added to the water to reduce surface tension and promote capillary flow as much as possible.

The tanks were rotated to eight discreet positions during the rollover simulation. 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 connections to the tank systems were inspected to ascertain the design features or components that may have influenced the amount of leakage observed. The inspections included internal features that could only be accessed by cutting the tanks open

The leak tests results are summarized in Table 9.

Table 9: Summary of tank leak test results.

Vehicle	Tank Orientation (degrees)							
	0	60	90	120	180	210	270	300
Honda Accord	N	Y	Y	Y	Y	Y	Y	N
Audi A8	Y	Y	Y	Y	Y	Y	Y	Y
BMW 325i	N	N	N	N	Y	Y	Y	Y
Chevrolet Corvette	Y	Y	Y	Y	Y	Y	Y	Y
Chrysler Cirrus	N	N	N	N	N	N	N	N
Dodge Neon	N	N	N	N	N	N	N	N
Ford Mustang	N	N	N	N	N	N	N	N
GMC Sierra	N	Y	Y	Y	Y	Y	Y	Y
Honda Odyssey	N	Y	Y	Y	Y	Y	Y	N
Jeep Cherokee	Y	N	N	Y	Y	Y	Y	Y
KIA Spectra	N	N	N	N	N	N	N	N
Mazda MPV	Y	Y	Y	Y	Y	Y	Y	Y
Mercury Grand Marquis	N	Y	Y	N	N	N	N	Y
Plymouth Grand Voyager	N	Y	Y	Y	Y	Y	Y	Y
Toyota Camry	Y	Y	Y	Y	Y	Y	Y	Y
Toyota Corolla	Y	Y	Y	Y	Y	Y	Y	Y
Toyota Prius	N	Y	Y	Y	Y	Y	Y	Y
VW Jetta	N	Y	Y	Y	Y	Y	Y	Y
Mercedes S430	Y	Y	Y	Y	Y	Y	Y	Y
Saturn SL	N	N	N	N	Y	Y	Y	Y

The following general observations were derived from a review of the fuel system leak tests:

- None of the tank systems leaked if the fuel lines and hoses remained intact. Leakage only occurred when a fuel line was disconnected. Lines and hoses were disconnected one at a time.
- For the most part, all of the leakages observed in the tank system rollover tests were greatly in excess of the 28 g per minute which is the maximum rate permitted in the FMVSS 301 standard.
- Leakage that occurred in the upright (0^o) orientation stemmed from lines and hoses that were connected to the tank below the fluid fill level. This is commonly referred to as "siphoning."
- In some cases the leakage rates reduced after several minutes due to a vacuum build up in the ullage of the tank.
- Six tanks leaked in each of the tank orientations.
- Four tanks did not leak in any combination of severed hoses and tank orientation.

TANK INSPECTIONS

The use of some technologies identified earlier was difficult to ascertain from the vehicle inspections without the ability to disassemble the vehicle. The tank component inspections allowed for their determination.

Filler Check Valves

A check valve was installed inside 15 of the 20 leak tested tanks. The valves in 14 of those tanks were normally closed and would open under fluid pressure to allow for refueling. Reverse flow of the fuel would act to keep the valve closed. The check valve mechanisms observed can be divided into three categories; a spring loaded plunger, flap door mechanism and a ball/float arrangement. Examples of each type of valve mechanisms are shown in Figure 3.

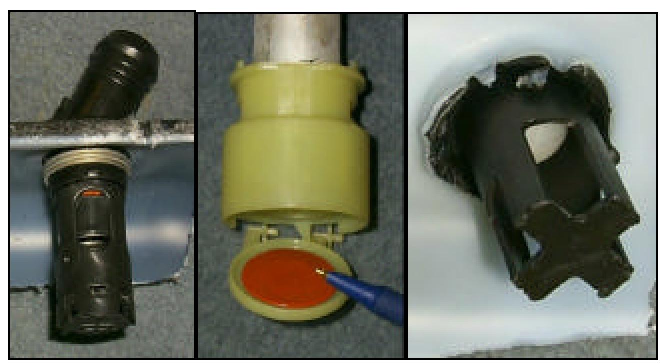

Figure 3: Check valve mechanisms from left to right: spring loaded, flap door and float type.

A plunger style check valve was found in 7 vehicles of which only the valve from the VW Jetta exhibited leakage when the filler hose was disconnected. The flap style valves were also present in 7 tanks, however, only the Kia Spectra incorporated a rubberized seal and was successful at preventing fluid loss. All others leaked.

Of all the check valves observed, the ball float type valve found in the Jeep Cherokee was the only system in which the state of the valve was normally open, meaning that the filler tube would only be sealed if the ball was engaged, by gravity, rising fluid levels or the reverse flow of fluid. All of these circumstances would act to seat the ball in the filler tube opening to prevent reverse flow. In the single instance of its use, the ball float valve was ineffective at preventing leakage when the tank was inverted.

The GMC Sierra tank did not incorporate a check valve. However, its filler tube was routed inside a larger tube which acted as the tank filler vent. Inside the tank the filler tube extended to the far side of the tank, therefore, depending on the tank orientation and fluid level this filler tube configuration may prevent fuel spillage. A cut-away view of the Sierra tank is shown in Figure 4.

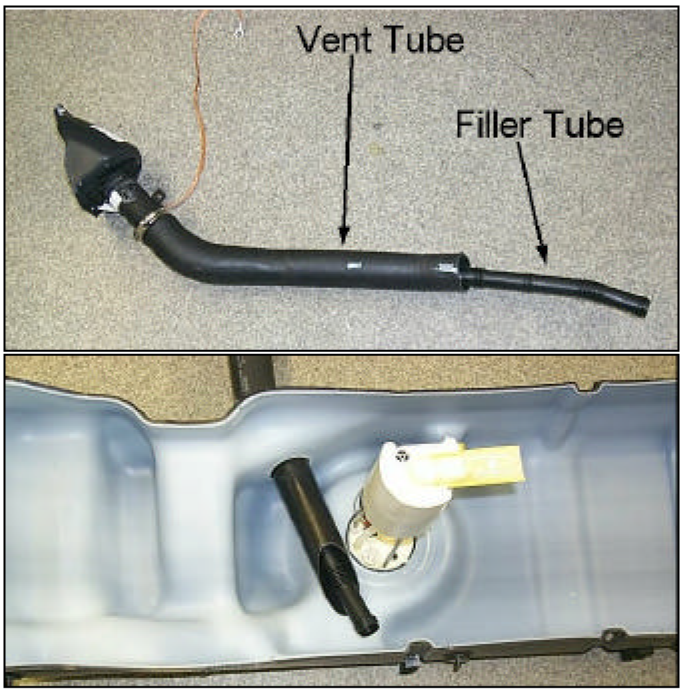

Figure 4: Filler tube arrangement from the GMC Sierra.

An additional valve flap type valve in the filler tube just behind the gas cap was present in 12 fuel systems. The valves are physically opened by the fuel nozzle of the gas pump during refueling. An additional 4 systems incorporated such a valve in the filler tube closer to, but still exterior to, the tank. With these systems the fuel pressure is sufficient to open the valve during refueling. These valves restricted flow yet none was effective at preventing reverse flow of fluid out of the tank during the rollover leak testing. This suggests that their purpose may be for vapor entrapment for emissions reduction.

Rollover Valves

Vents on the top of the tank allow for pressure balancing either to prevent suction in the ullage when fuel is consumed during vehicle operation or conversely to prevent excessive vapor pressure build-up. In some cases the pressure equalization may be controlled with diaphragm valves to maintain the ullage pressure at predefined design specifications. These vents are normally connected to a vapor canister to ensure vehicle compliance with environmental emission requirements.

If no countermeasures were incorporated to prevent fuel leakage through the vent lines and hoses when a tank was inverted, as in a vehicle rollover, leakage would certainly occur. With mandatory compliance with the FMVSS 301 standard, which limits allowable fuel leakage during vehicle inversion following a crash test, it is not surprising that all the tank systems inspected were fitted with rollover valves to prevent leakage.

Typically the rollover valves were normally opened, and under the influence of gravity and/or fluid flow the valves would seal. Springs or shifting ballast were two means by which the sensitivity of the valves to inversion was increased, thereby, decreasing the critical angle required to close the valves. When dry, the valves would engage as they approached approximately 70º to 90º rotation from their normal upright position. In many cases it was observed that friction prevented the valves from engaging in a repeatable manner. However, it is likely that lubrication provided by the gasoline would reduce the friction and coupled with the buoyancy of the valve plunger and the flow pressure, would enable the valves to engage sooner. Three of the rollover valves encountered are shown in Figure 5.

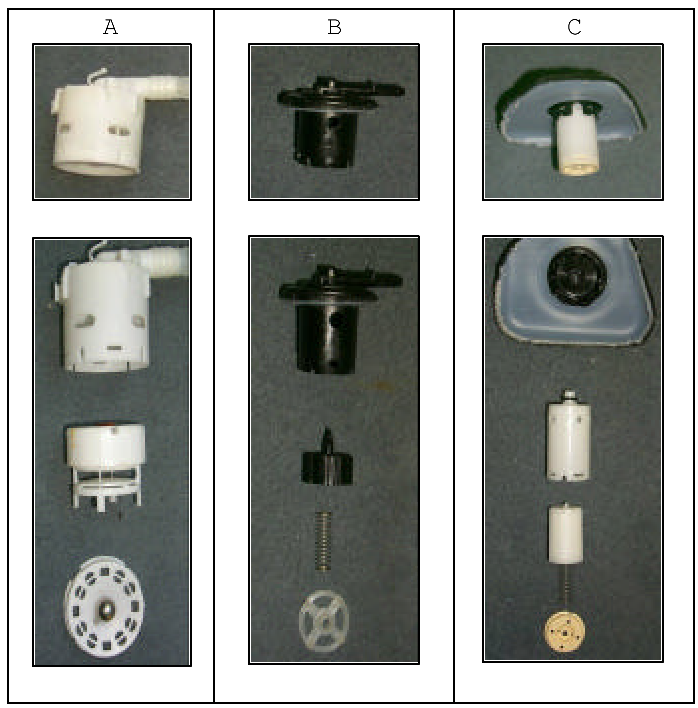

Figure 5: Examples of rollover valves from: a) Mercedes S430, b) Dodge Neon and c) Honda Odyssey.

The rollover valve designs encountered all appeared to be effective at preventing fuel leakage when their tanks were inverted. Nevertheless, for both the Audi A8 and the BMW 325 tanks, excessive leakage was recorded at various inversion angles. Although the rollover valves for these vehicles appeared to function they were located on a secondary reservoir or expansion tank at a remote location to the main tank and it was the vent hoses connecting the tanks that leaked when severed. These vent hoses connected directly to the main tank without the benefit of a rollover valve.

Sending Unit Connections

The connections to the sending unit leaked during tank inversion in 11 of the tanks systems tested. These connections included, where applicable, the fuel delivery line to the engine and one or both of the following: the fuel return and/or the sender vent return.

Typically, the fuel pump is placed inside the tank; therefore, leakage from this line would suggest that the pump does not seal the delivery line if the pump is not energized. Of the sending units that leaked, only one did not leak from the fuel delivery line. Additionally, the only tank system with the fuel pump located exterior to the tank leaked profusely from the fuel delivery line exiting the tank.

Of the 11 sending unit designs that leaked, 7 of them incorporated a fuel return line, each of which also leaked. Furthermore, the two sending units that included a sender vent return line leaked from that connection.

The 9 sending units that did not leak when inverted were comprised of either one or two fuel line connections but did not include a sender vent return line. With these sending units, the pump prevented fluid flow when not operational and the fuel return line was routed through a check valve or rollover type valve.

These designs demonstrate that with the proper pump design and selection of valve components sending units can be made to prevent fuel leakage if the fuel lines and hoses connected to it are damaged or severed.

Overall Tank Design

The crashworthiness of a gas tank and its installation is of significant importance to preventing post collision fuel leaks. If, however, the tank is undamaged and the fuel lines or hoses are damaged then the possibility of post crash fires occurring may still exist, unless the tank system is designed to prevent this leakage.

The ability to design such a tank was evident from the results of the leak testing on 4 of the tank systems summarized previously in Table 9. These tank systems proved that it was possible to design connections and fittings to the tank that would not leak if the lines and hoses connected to them were severed. Interestingly, the tanks were obtained from mid to low end vehicles, which suggests that a “spill” proof tank does not require advanced or expensive technology to be achieved. Additionally, in comparison to several other tanks evaluated in the test series, these tanks were of simple design with 4 or 5 lines and hoses connected to them, compared to other tanks systems which had from 6 to 11 fuel hose connections.

It should be noted that there were tank systems with 4 to 5 hose connections that did leak. However, limiting the number of connections to a tank may reduce the opportunity for a fuel line or hose to be damaged in a collision.

Ultimately, what is important for tank design considerations is that each line emanating from the main tank must have a spill prevention device such as a rollover valve or a check valve installed. The tanks that passed the leak test in all orientations complied with this principle.

As an example of non-compliance with this principle, ten of the tanks inspected did not employ a rollover valve on the filler vent. Consequently, in these instances a severed line essentially equates to a hole directly into the tank.

SUMMARY AND CONCLUSIONS

A database comprising information related to the fuel systems of 89 vehicles from the North American fleet has been compiled. The vehicles contained in the database were matched with their sister models and corporate cousins and in so doing the number of vehicles represented by the database increased to a total of 129 vehicles. The resulting percentage of total 2003 North American vehicle sales represented by the database is 79%.

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 database can be used for the analyses of accident trends pertaining to the incidence of post crash vehicle fires particularly related to the fuel system or to the service battery. Further, by grouping vehicles with common features it may be possible to ascertain the strengths and/or weaknesses of a fuel system design feature with respect to the common industry practice. If combined with accident statistics, the information in the database can potentially be used to identify tank design features or specifications that enhance a fuel system’s crashworthiness.

A review of fuel system fire safety technologies with possible applications in the automotive, aviation and military industries was undertaken. In principle, all the technologies identified can be incorporated into a fuel system’s design, however, the cost or suitability of doing so for a given application would have to be determined.

Leak testing and additional component inspections on a subset of twenty fuel systems from the vehicle database were performed. The leak testing comprised rotating the tanks to eight discreet positions. In each position the fuel system hoses were disconnected one at a time to represent damaged or severed lines or hoses and the resulting leakage rates were observed. In summary the test results showed that:

- none of the tanks leaked if the lines and hoses were intact,
- 4 tanks did not leak in any orientation,
- 6 tanks leaked in every tank orientation.

Inspection of the tank components identified the use of filler check valves in 15 of the 20 tanks inspected. Three styles of valves including spring loaded plungers, flap door mechanisms and ball/float arrangements were identified. Generally, the spring loaded plungers were effective at preventing leakage while the others were not.

Flap valves exterior to the tank were present in 16 tank filler tube assemblies. These valves restricted flow but none prevented fluid from leaking out of the filler tube, suggesting that their purpose is for vapor entrapment for emissions reduction.

Likely as a consequence of the implementation of the FMVSS 301 standard, all tank systems evaluated employed a rollover valve on the tank vents employed for regulating the pressure in the ullage of the tank. Many rollover valve designs were encountered and if installed on or inside the tank all appeared to be effective at preventing fuel leakage when the tank was inverted. Although the valves themselves if installed remotely from the main tank may have prevented fluid loss, leakage from the connection to the tank was still possible.

Leakage from the sending unit connections was observed in 11 of the tank systems tested. For the 9 sending units that did not leak, the pump prevented fluid flow when not operational and the fuel return line was routed through a check valve or rollover type valve. These designs demonstrate that with the proper pump design and selection of valve components, sending units can be made to prevent fuel leakage if the fuel lines and hoses are damaged or severed in a crash.

The 4 tanks that did not leak in any orientation demonstrate that it is possible to design connections and fittings to a tank that will not leak if the hoses connected to them are severed. Furthermore, the fact that these tanks were simply designed and came from mid to low end vehicles suggests that advanced or expensive technology is not required to achieve these results.

The results of the rollover leakage tests highlight the importance of incorporating leak prevention devices such as rollover valves and check valves in the tank for every line or hose emanating from the main tank. Fuel leakage prevention is a necessary requirement and must compliment the crashworthiness performance of vehicles to ensure that the risk of fuel fed fires is mitigated.

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