Fuel System Crashworthiness for Recreational Off-Highway Vehicles

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ABSTRACT

Recreational Off-Highway Vehicles (ROVs) are a distinct class of vehicles defined by an American National Standard (ANSI). The vehicles are intended primarily for recreational use and may have secondary general utility applications. The American National Standard (ANSI) for Recreational Off-Highway Vehicles addresses minimum requirements for aspects of ROV equipment and configuration, but includes no discussion regarding the design or performance of ROV fuel systems. The purpose of this study was to: survey pre- and post-ANSI Standard designs of ROV fuel systems; examine fuel system design recommendations and requirements for other types of fueled motive equipment, including diverse types of recreational equipment; and describe the environment in which the ROV was intended and the environment in which it was legal for use. SAE Standards, Recommended Practices and Information Reports for diverse human-operated fueled motive equipment from personal watercraft to motorcycles revealed numerous recommendations and requirements for fuel system design and performance. Observations of the sampled ROVs indicated that known and effective crashworthy concepts and features were not present on some fuel systems. Given the increasing popularity of ROVs, a combination of recommendations are proposed including that individual States discontinue the practice of registering ROVs for use on highways and that those that modify ROVs intended for on-road use adhere to the requirements of the Federal Motor Vehicle Safety Standards (FMVSSs). A new FMVSS is not proposed, but a minimum fuel system crashworthiness design and/or performance standard applicable to ROVs for their intended use should be considered.

INTRODUCTION

The National Traffic and Motor Vehicle Safety Act of 1966 authorized the establishment of the predecessor to the National Highway Traffic Safety Administration (NHTSA) and empowered the federal government to “prescribe motor vehicle safety standards for motor vehicles and motor vehicle equipment in interstate commerce.” Motor vehicle was defined as “a vehicle driven … and manufactured primarily for use on public streets, roads, and highways” [1].

Federal Motor Vehicle Safety Standard 301 - Fuel System Integrity (FMVSS301) was first issued in 1967 and intended to reduce injury and fatality due to fires that result from motor vehicle crashes. In its initial version FMVSS301 applied only to passenger cars and covered only impacts to the front of the vehicle. By 1977 the Standard was upgraded to expand performance requirements to rear, side and rollover crashes and extended requirements to light trucks (pickups, vans, multipurpose passenger vehicles, and buses) with gross vehicle weight ratings of 10,000 pounds or less [2].

In June of 1998 NHTSA published FMVSS500 - Low-speed vehicles. A low-speed vehicle (LSV) was defined as: “4-wheeled motor vehicle, other than a truck, whose speed attainable in 1.6 km (1 mile) is more than 32 kilometers per hour (20 miles per hour) and not more than 40 kilometers per hour (25 miles per hour) on a paved level surface.” The new safety standard for low-speed vehicles acknowledged the growing use and lawfulness of golf carts on low speed roads and was made consistent with NHTSA longstanding interpretation that vehicles like unmodified golf carts that were incapable of speeds above 20 mph were not motor vehicles that fell within its authority. Requirements for LSVs specify basic safety equipment and a maximum speed of 25 mph (40 kph) [3]. There are no FMVSS for any aspect of low-speed vehicle fuel systems.

As NHTSA's new FMVSS500 regulating the design of LSVs became effective, a new type of off-highway recreational vehicle was emerging in ever-increasing numbers. According to the American National Standard for Recreational Off-Highway Vehicle (ANSI/ROHVA 1-2010) [4], “Recreational Off-Highway Vehicle or ‘ROV’ means a motorized off-highway vehicle designed to travel on four or more tires, intended by the manufacturer primarily for recreational use by one or more persons and having the following characteristics: a steering wheel for steering control; non-straddle seating; maximum speed capability greater than 35mph (56.3 km/h); Gross Vehicle Weight Rating (GVWR) no greater than 1700 kg (3750 lbs); less than 2030mm (80 in) in overall width, exclusive of accessories; engine displacement of less than l,000cc (61ci); [and] identification by means of a 17 character PIN or VTN” [4, 5]. According to the stated Scope of ANSI/ROHVA 1-2010, the standard is specific to ROVs as defined and does not apply to a listing including: vehicles described by common names like “Dune Buggies,” “Rock Crawlers,” “Sand Cars,” “Sand Rails,” “Off-Road Go Karts,” “Trophy Karts,” and “Mini-Trucks” vehicles that comply with FMVSSs; vehicles defined by a list of four ANSI standards and a draft ANSI standard; part of an ISO standard applicable to Burden and Personnel Carriers; and SAE standards for Utility Vehicles and Low Speed Vehicles [4]. The Recreational Off-Highway Vehicle Association (ROHVA) was an industry trade association supported by ROV manufacturers[1]. Figure 1 shows a picture of an ROV.

Figure 1. A Recreational Off-Highway Vehicle (ROV).

Federal Motor Vehicle Safety Standards are not applicable to ROVs because they are sold as off-highway vehicles, yet States that regulate the operation of motor vehicles on public roads often register ROVs for on-road use. For example, the State of Arizona offers motor vehicle registration authorizing highway use to owners of off-highway vehicles that meet all on-highway equipment requirements [6]. The State of Arizona equipment requirements include elementary safety equipment but no crashworthiness requirements [7]. The only Arizona provision regarding the fuel system requires that the “filling spout for the fuel tank is properly closed by means of a cap or cover composed of a noncombustible material that meets or exceeds applicable federal safety standards” [8]. The Insurance Institute for Highway Safety's (IIHS) lists 18 states that allow a class of vehicles, called minitrucks and sold as off-road vehicles, to be driven on public roads to farm or construction sites [9].

In 2008 NHTSA denied three petitions to create a new class of medium-speed vehicles (MSV) [10]. Medium speed was suggested as a maximum speed of 35 mph. Two of the three petitions contemplated limited crashworthiness requirements for medium speed vehicles. One of the petitions specifically suggested that compliance with FMVSS301 be required if the MSV was equipped with a fuel tank. Analysis performed by NHTSA supported its conclusion that the traffic environment in which MSVs would travel required the full set of FMVSS to prevent fatalities and serious injuries. In discussing its denial NHTSA officials thought it was neither necessary nor appropriate to significantly increase the risk of death and serious injury to save fuel. The IIHS lists nine states that allow medium-speed vehicles on portions of their public roads [11].

In October of 2009 the U.S. Consumer Products Safety Commission (CPSC) announced that it was considering whether there may be unreasonable risk of injury or death associated with ROVs and published an Advanced Notice of Proposed Rulemaking (ANPRM) under the Consumer Product Safety Act [12]. The CPSC is an independent federal regulatory agency that was created in 1972 by the U.S. Congress and directed to “protect the public against unreasonable risks of injuries and deaths associated with consumer products” [13]. In its ANPRM the CPSC noted that in 1998 fewer than 2,000 ROVs were sold by one manufacturer; by 2003, when a second manufacturer entered the market, almost 20,000 ROVs were sold and by 2008, more than 126,000 ROVs were sold by over a dozen manufacturers and distributors [12]. The CPSC solicited comment and information on topics related to potential regulation or voluntary standards addressing dynamic

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[1] The Recreational Off-Highway Vehicle Association (ROHVA) was formed to promote the safe and responsible use of recreational off-highway vehicles (ROVs) manufactured or distributed in North America. ROHVA is accredited by the American National Standards Institute (ANSI) to develop a standard for the equipment, configuration and performance requirements of ROVs. Based in Irvine, Calif., the not-for-profit trade association is sponsored by Arctic Cat, BRP, Kawasaki, Polaris, and Yamaha. http://www.rohva.org/Default.aspx. Downloaded October 19, 2011.

stability, handling characteristics, and occupant protection characteristics for ROVs.

In March 2010 the ROHVA obtained approval of the first standard in the world for ROVs from the American National Standards Institute (ANSI) [14]. According to ROHVA's web site, “over a period of 26 months, the ROHVA Technical Advisory Panel worked expeditiously to develop the ANSI standard, analyzing and debating the complex issues and competing objectives associated with this unique class of vehicles” [14]. As of May 2011 the CPSC was participating in voluntary standard activities related to ROVs through revision of the ROHVA's ANSI Standard for Recreational Off-Highway Vehicles, ANSI/ROHVA 1-2010, and development of the Outdoor Power Equipment Institute (OPEI) ANSI Standard for Multipurpose Off-Highway Utility Vehicles, ANSI/OPEI B79.1-20XX [15]. After reviewing a canvass copy of draft proposals the CPSC staff commented that the revised and proposed standards did not adequately address vehicle stability, vehicle handling, and occupant protection performance [15]. The 2010 ANSI Standard for ROVs does not address any aspect of fuel system performance or fuel system crashworthiness.

In summary, continued CPSC participation in ROV design and performance standard activities, NHTSA regulation of on-highway vehicle manufacture and state regulation of on-highway vehicle use highlight the danger that fuel system crashworthiness features may mitigate. This paper summarizes a survey of SAE Standards, Recommended Practices and Information Reports relating to fuel system crashworthiness of diverse fueled motive equipment. Examples of design features that implicate fuel system crashworthiness in several ROVs are illustrated. Features of the crash environment are defined and the author concludes with recommendations for establishing practices that may be considered in future standard development.

SAE GROUND VEHICLE STANDARDS, RECOMMENDED PRACTICES AND INFORMATION REPORTS

There are SAE Standards, Recommended Practice and/or Surface Vehicle Information Reports for a variety of fueled, engine driven equipment with provisions that can be construed as having some fuel system crashworthiness features. These SAE documents from the 2008 SAE Handbook include: SAEJ2046 - Personal Watercraft Fuel Systems; SAEJ1241v002 - Fuel and Lubricant Tanks for Motorcycles; SAEJ2358 - Low Speed Vehicles; SAEJ703 - Fuel Systems - Truck and Truck Tractors; SAEJ288 - Snowmobile Fuel Tanks; and SAEJ2587 - Optimized Fuel Tank Sender Closure. A cancelled SAE Surface Vehicle Information Report, SAEJ1664 -Passenger Car and Light Truck Fuel Containment, described fuel containment integrity principles and guidelines. [16, 17, 18, 19, 20, 21, 22]

The SAE Surface Vehicle Information Report, SAEJ1664 - Passenger Car and Light Truck Fuel Containment, was cancelled in March of 2002, according to SAE records because “it was no longer needed” [23]. SAE's definition of a cancelled report is: “a technical report that is no longer actively being used. A cancelled technical report may be superseded by another technical report. A cancelled action requires Committee and Council level ballot” [24]. The Information Report was first published January 1, 1994 after approval by consensus ballot by the SAE Fuel Containment Standards Committee and included nine pages of recommendations organized as three principals and 15 guidelines. Guidelines covered a wide range of topics from durability to manufacturing to containment integrity. Only the collision damage principal and containment integrity guideline were utilized.

Review of SAE Standards, Recommended Practices and Information Reports relative to ROV fuel system crashworthiness revealed specific provisions and exact language that related to fuel system crashworthiness. In some cases the provisions of an SAE document did not specifically state that its purpose was for crashworthiness, but a judgment was made by the author that the provision would result in a feature that affected crashworthiness.

Identified sections of SAE Standards, Recommended Practices and Information Reports from the 2008 SAE Handbook are included in Appendix A. The documents revealed numerous recommendations and standards for fuel system crashworthiness design and performance. Many of the recommendations and standards specified both prescriptive requirements and performance requirements. The most common prescriptive requirements in SAE fuel system documents dealt with fuel line material and fuel line attachments. The fuel line specifications did not provide performance requirements that described minimum forces or impact loads. Only the recommended practice for trucks and truck tractor fuel tanks provided specific prohibitions on the location of the fuel tank, including that no part of the fuel system may be located within or above the passenger compartment, extend beyond the widest part of the vehicle or be located forward of the front axle.

Vehicle types that had unique fuel system exposures were regulated by SAE standards that prescriptively dictated specific attributes in addition to performance specifications. The recommended practices for both motorcycle fuel and lubricant tanks and truck and truck tractor fuel systems were described by special prescriptive requirements tailored to the unique utility and design of the equipment. For example, the motorcycle fuel cap requirements called for a smooth contour and a rear located hinge for caps or cap covers in anticipation of the unique loading that the straddled fuel tank sustained as a driver moves forward relative to the tank in a frontal crash. Likewise, crossover fuel lines and bottom fittings had special required attributes in the truck and truck tractor Recommended Practice. Prescriptive specification of an attribute is contrasted to the FMVSS301, which is solely a performance standard.

The most common performance requirement in SAE fuel system standards was some form of fuel tank roll or pitch test that specified a minimum leakage rate when the tank was filled and oriented other than upright. Another common performance requirement was some form of impact or deceleration test. The Recommended Practice for fuel and lubricant tanks for motorcycles specified a longitudinal deceleration test at 16.3 mph (7.3 m/s) and a lateral impact pendulum test of 80 lbs to 160 lbs (36 kg to 74 kg) producing 450 in-lb of kinetic energy [the equivalent pendulum impact speed is in the range of 7.8 mph to 11.2 mph (3.5 m/s to 5 m/s)]. The motorcycle lateral impact test anticipated an impact penetration unique to motorcycles where the rider's knee would be push sideways into the straddled fuel tank. The Recommended Practice for truck and truck tractors fuel systems specified two different drop tests required by Federal Motor Carriers Safety Regulations. Leakage performance for all SAE Standards or Reports and FMVSS301 were typically specified at less than one ounce during impact and one ounce per minute following impact.

EXAMPLES OF ROV DESIGN FEATURES

Using the collision damage principle and containment integrity guidelines of the cancelled SAE Surface Vehicle Information Report, SAEJ1664 - Passenger Car and Light Truck Fuel Containment, as a guide three types of crash-induced fuel containment system failure modes were considered [22]. The three failure modes included: (1) rupture failures due to the fuel tank location, mounting, shape and material properties; (2) filler neck and/or other component separations including the fuel cap and fuel lines; and (3) puncture failures due to intrusion of components in the fuel containment system's environment. The author has used the collision damage principle and containment integrity guidelines of SAEJ1664 for identifying and organizing fuel system crashworthiness features in other prior published works that examined crash induced failures of pickup truck side mounted saddle fuel tanks [25] and police cars [26].

The collision damage principle was, “[An ROV] and its fuel containment system are subject to collision damage in an infinite variety of situations including various angles, speeds, and fixed or moving objects impacted, multiple impacts, and rollovers with or without preceding or subsequent impacts” [22]. Speed, considered in the context of the collision damage principle, was consistent with the ROHVA definition: “maximum speed capability greater than 35 mph.” In assessing features related to ROV fuel containment system crashworthiness failure risks no tests were performed and no tests were reviewed that documented ROV fuel system performance.

Four different ROVs were examined. The ROVs included two vehicles from model year 2006, one from model year 2011, and one from model year 2012. All of the vehicles were examined with their fuel systems in OEM condition. All of the vehicles were in used condition.

FEATURES RELATED TO RUPTURE RISK

Each ROV fuel tank was located under the right side-by-side seat. This location placed the tank laterally between the mid-vehicle mounted engine and structures at its right side. Each fuel tank filled from the right side of the vehicle. Each tank was nominally rectangular in shape with a tank volume of around eight gallons. Because of the size and location of each tank the right side of the tank was within several inches of right structural components and located forward of the rear wheel well. Each tank was also essentially against the floor of the vehicle.

An example of tank location and position relative to structures is shown in the top view of figure 2 and rear view of figure 3. Three of the tanks were plastic material and one tank was tern-plated steel. The specific material description of one plastic tank was High Density Polyethylene with an Ethylene Vinyl Alcohol permeation barrier. Two of the ROV fuel tanks had fill pipe attachments that eliminated vapor space because the fill pipe attached at the top surface of the fuel tank. An example of a fill pipe attachment that enters below the top of the tank, preserving vapor space, is shown in figure 4.

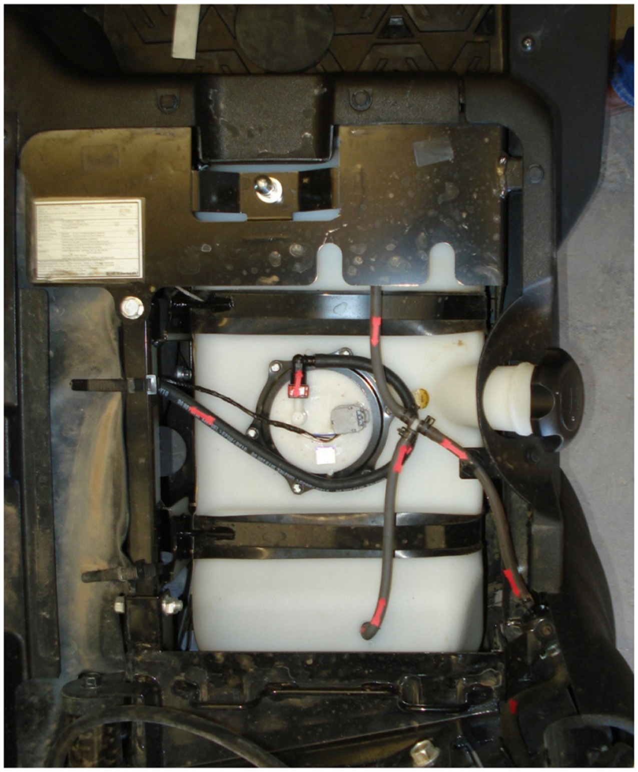

Figure 2. An example of tank location and position relative to structures, shown from top view.

Figure 3. An example of tank location and position relative to structures (covers removed), shown from rear view.

Figure 4. An example of a fill pipe attachment that enters below the top of the tank, preserving vapor space.

FILLER NECK AND OTHER COMPONENTS FAILURE RISK

Each tank was filled from the right side. Three of the fill pipes attached principally on the right side of the tank and one attached at the back of the tank. Each attachment was integral to the tank, in other words there were no interconnecting fuel hoses and clamps. All of the fuel containent systems had fuel caps at the end of fill pipes. None of the fill pipes were fitted with one-way flow valves. On the steel tank the filler pipe was welded raising concern that absent proper attention heat induced localized changes in material properties may render the attachment joint weak if deformed. Each fill pipe was relatively short ranging from two to five inches. The pipe was short because of the close proximity of the tank to the side of the vehicle.

Fuel caps were located at the side of the vehicle under a variety of conditions. All caps were unvented and without pressure relief features. All caps were plastic and required multiple turn screw-on attachments. Three of the caps had integral cover, seal and attachment by threads on the outside of the filler pipe, as shown in figure 5. One of the integral caps also incorporated a fuel level gauge that was viewable behind a circular clear plastic window. The mechanism of the gauge allowed liquid gasoline to freely move through a small hole and accumulate between the gauge's display and clear plastic cover (figure 6). The remaining cap had a common passenger car or light truck crashworthiness feature and possessed a frangible cover that if broken away left the seal and attachment by threads internal to the filler pipe (figure 7).

The ends of the fill pipe and fuel caps were positioned at the side of the vehicle with varying degrees of exposure to direct contact and guarding. Direct exposure was documented where the cap protruded beyond nearby steel structures that might prevent broad intrusion. For example, if the vehicle rolled onto its side the vehicle in figure 8 would allow interference between the ground and fuel cap. A design that demonstrated greater protection located side structures in close proximity and substantially outboard of the fuel cap, as seen in figure 9. Steel tubes attached to a removable seat appeared to include features that may protect a fill pipe and fuel cap that would otherwise be exposed (figure 10). The author was concerned that the seat-mounted steel tubes shown in figure 10 may not sufficiently protect the fuel cap given the seat's strength and method of attachment to the ROV structure.

Other closures of the fuel tanks included sender units, fuel lines and vents. The plastic fuel tanks each had a sender unit held in place with screws, while the steel tank had a cam-locking sender unit attachment. Fuel lines consisted of tubes covered with braded steel or tubes of reinforced rubber. In all cases fuel tube assemblies were clamped in place on barbed spuds or used quick connector fittings. Vent lines were present on all tanks, though not always clamped.

Tank venting was executed by a variety of means. One tank simply vented from the top of the tank through a short opaque tube, as pictured in figure 11. This method would allow an inverted tank to readily leak liquid fuel. The other three fuel tanks employed venting schemes that ultimately vented to atmosphere, but in series with rollover valves and/or other inline mechanisms. A fuel tank integrated rollover valve is shown in figure 12.


Figure 5. Three of the caps had integral cover, seal and attachment by threads on the outside of the filler pipe.

Figure 6. Gauge mechanism allowed gasoline flow through small hole which accumulated between the display and plastic cover.


figure 7. Cap with frangible cover that if broken away left the seal and attachment to threads internal to the filler pipe.

Figure 8. If the vehicle rolled onto its side, interference between the ground and fuel cap would occur.

Figure 9. Side structures in close proximity and substantially outboard of the fuel cap.

Figure 10. Steel tubes attached to a removable seat appeared to protect a fill pipe and fuel cap that would otherwise be exposed.

Figure 11. Vent from the top of the tank through a short opaque tube.

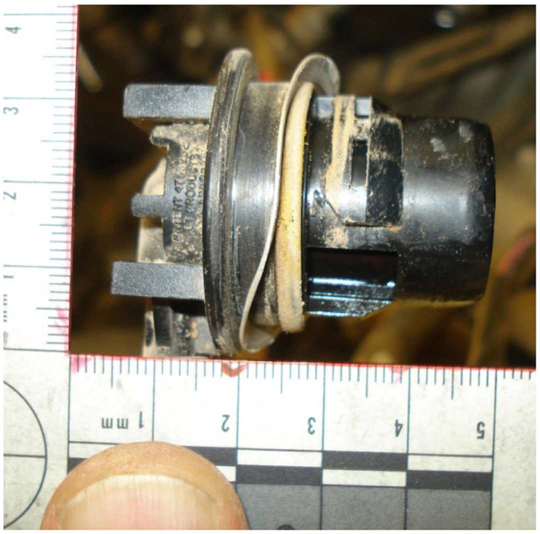

Figure 12. Fuel tank integrated rollover valve.

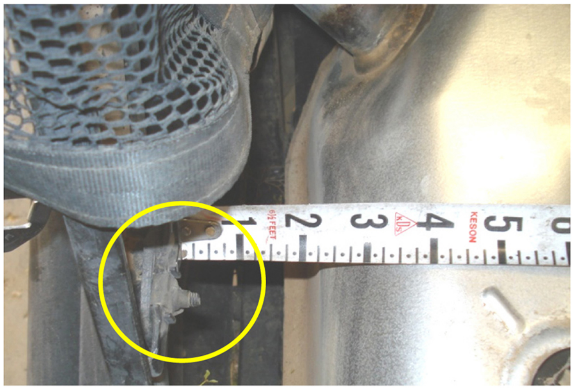

Figure 13. Example of sharp objects in close proximity to ROV fuel tank.

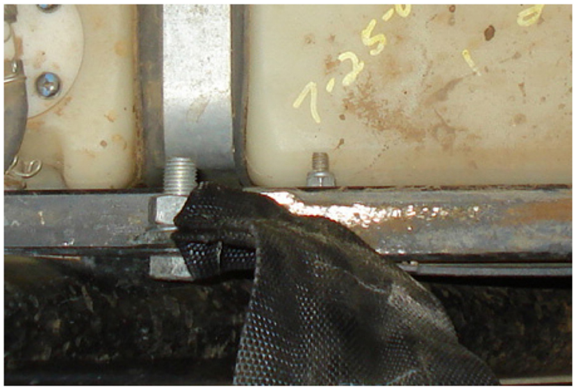

Figure 14. Examples of sharp objects in close proximity to ROV fuel tank.

Figure 15. Examples of sharp objects in close proximity to ROV fuel tank.

FEATURES RELATED TO PUNCTURE RISK

Sharp components were documented in close proximity to the fuel tanks. These components include bolt heads, screw ends and sharp steel brackets. Figures 13, 14, 15 illustrate several examples of sharp objects in close proximity to ROV fuel tanks.

Purposeful impact shielding of the fuel tanks or shielding of structures surrounding the tanks was not obviously present. Each tank was shielded from beneath by a steel plate that covered the bottom of the vehicle. The authour was concerned that the fuel tanks may have been susceptible to penetration from objects external to the vehicle given the proximity of the tanks to the side. The tank areas were enclosed by plastic and steel covers that primarily served as a cosmetic versus protective feature.

DISCUSSION

Limited crash statistics were available regarding the exposure of ROV occupants to fatal or serious injury on public roads. Though incidents involving fire and linked to ROVs were known to have occurred, there was no known published compilation of crashes that might assist in understanding the field performance of ROV fuel system crashworthiness. The crash statistics presented by NHTSA in its denial of a safety standard for medium-speed vehicles (MSV, vehicles with maximum speed of 35 mph) noted that on average between 2002 and 2006 in vehicles that were certified to comply with FMVSSs 6,319 occupants were killed on roads with posted speed limits of 35 mph or less, and 13,493 were killed on roads with speed limits of 45 mph or less [10]. Using its published methodology [27], NHTSA estimated that in 2005, on roads with a posted speed limit of 35 mph or less 1,921 crash victims lived because the vehicle they were riding in complied with all FMVSSs. In crashes on roads posted at 45 mph or less, 3,163 lives were saved because the vehicles involved were compliant with all FMVSSs[2] [9]. A comparison to medium-speed vehicles on roads with 35 mph and 45 mph speed limits makes sense in that ROVs are by definition capable of speeds in excess of 35 mph and more likely to be operated on roads or restricted to roads with lower speed limits[3]. The NHTSA MSV statistics are not specific to fires. Translating NHTSA's MSV analysis to ROVs indicates directionally the benefit of FMVSSs, but it may not be valid to extrapolate results of passenger car crashes to crashes of ROVs given differences in intended use, vehicle design, weight, crash scenarios and occupant exposure to injury and entrapment.

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[2] In 1990 NHTSA estimated that FMVSS301 reduced fires in all passenger car crashes by 14 percent; this translated to 3,900 fewer fires annually for an entire fleet upgraded to the requirements of the Standard. However, NHTSA reported no statistically significant reduction in burn injury or burn death [2]. In 2004, NHTSA estimated that safety technologies saved 328,551 lives between 1960 and 2002 and noted effectiveness trends that included: not much effect before FMVSSs; steady growth in effectiveness as the early non-belt FMVSSs phased in; an effectiveness growth interruption attributed to declining belt use; and, more recently, steadily increased effectiveness from increased belt use, air bags and more recent FMVSSs [27].

The risk of fire in ROV incidents is not well defined. According to a September 2009 CPSC staff report, 181 ROV-related fatality and injury incidents occurring between January 2003 and August 2009 were reported [28]. The CPSC data are counts of reported incidents. The incidents are not statistically-derived and are not presented as rates per unit of exposure (per hours of use, per miles traveled, per registered vehicle, etc.). The top two incident types were rollover (125, 69% of reported incidents) and collision (20, 11% of reported incidents). The third most common incident was mechanical incidents for which nine (5% of reported incidents) were identified. Mechanical incidents included incidents where the vehicle was reported to have caught fire, including one incident where the ROV was reported to have overturned and then caught fire. The CPSC report does not specifically enumerate the number of fires among the mechanical incidents, nor does the report provide detail regarding occurrences of fire with burn injury. Overturning incidents included those where the vehicle was reported to have rolled forward, backward, sideways, or in an unknown direction. Overturn incidents were not preceded by a collision and occurred on level ground and grades. Collision incident meant the ROV struck (or was struck by) another vehicle or the ROV struck a stationary object (e.g., rock, tree, gate, etc.). In some collision incidents, collision of the ROV with an object or with another vehicle was then followed by the overturning of the ROV.

In a May 2011 update, CPSC staff described review of 329 reports of ROV-related fatality and injury incidents that occurred between January 2003 and September 2010. The reports included 169 fatalities and 299 injuries. A significant hazard pattern for ROV-related incidents was reported to involve a quarter turn lateral rollover of the vehicle [15]. A dominant lateral quarter turn rollover is the type of rollover documented in testing reported in 2011 by Ohio State University and Scientific Expert Analysis (SEA) in which significant sliding of the ROV on the ground occurred [29]. A roll simulator developed in relation to the Ohio State University and SEA test had a translational speed of 22 ft/s (15 mph) [30]. If fuel containment components protruded beyond protective structures and guarding or shielding was inadequate, abrasion in the ground contact could cause fuel leakage.

Though rates of fire incidents are not well defined, but roll-overs and collisions are anticipated, minimum practices for fuel system crash performance proportional to the risk of ROV fire and/or risk of ROV burn injury and burn death should be implemented. The risk of ROV fire and/or risk of ROV burn injury and burn death is meant by the author to be a net quantity after combining the ROV crash fire exposure and crash fire consequences. The concept of proportionality to risk is intended to be conceptually equivalent to subjective terms in use by other design and performance standards or recommended practice. For example (emphasis added) the current SAE standard on sender unit closures dictates, “It is the responsibility of the vehicle OEM to assess all aspects of the fuel tank and vehicle design to assure the integrity of the fuel system in the event of *reasonably* severe vehicle impacts” [21]. Likewise, the CPSC was created by the U.S. Congress and directed to “protect the public against *unreasonable* risks of injuries and deaths associated with consumer products” [12]. Finally, the ANSI/ROHVA 1-2010 Standard under general requirements of owner's manuals states, “Every manual shall be written and designed in a manner *reasonably* intended to convey information regarding safe operation and maintenance of the vehicle” [4]. In each example the term reasonable (or unreasonable) is used.

The usage of terms like reasonable (unreasonable) or proportional to the risk are in the author's opinion designed to accommodate diversity, competition, ingenuity, advancement of the state-of-the-art and, importantly, human judgment. In addition, the term provides that minimum generally accepted provisions will be part of all design practice, and that cutting edge or provisions with disproportional cost, unreasonable utility altering effects or unproven benefit can reasonably be excluded. Minimum generally accepted provisions of a fuel system design practice would be consistent with the requirement in every surveyed SAE Standard for fueled motive equipment requiring minimum leakage in roll testing. On the other hand, based upon uncertainties in current crash statistics regarding potential or actual burn causation in ROV incidents, provisions requiring fire suppression should be excluded. Minimum performance may be described in a best practice guideline or standard or could be incorporated into existing provisions.

CONCLUSION

Given the increasing popularity of ROVs, their manufacture as off-road vehicles and their intended use primarily for recreational and secondarily for general utility applications, it is recommended that individual states discontinue the practice of registering ROVs for use on highways and that modified ROVs intended for on-road use adhere to the requirements of the FMVSSs.

Minimum design practices should be based upon a finalized examination of the crash exposure of ROVs. Based upon the discussed compilation of 181 reported incidents, the most

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[3] Current crash test requirements in FMVSSs are also in the range of speeds that an ROV may operate on public roads; this comparison was also made by NHTSA relative to MSVs [9]. For example the front barrier crash requirements of FMVSS301, the fuel system integrity standard, requires a frontal barrier impact that simulates a 30 mph crash between the test vehicle and a vehicle like itself. In the current traffic mix it is more likely that in a frontal crash an ROV would be hit by a vehicle weighing more than itself. The current side impact requirements of FMVSS301 simulates a crash in which the tested vehicle traveling at 15 mph was struck in the side by a light vehicle traveling at 30 mph. The current rear impact requirements of FMVSS301 are at 50 mph. All impacts are followed by a static rollover test.

frequent and more understood incidents are overturn crashes which account for 69% of incidents. Overturn crashes are dominantly lateral quarter-turn rollovers. Though specifics of their exposure are not adequately described, eleven percent of incidents were collisions. A minimum fuel leakage practice should be specified for the crash and post crash phases. For ROVs intended for on-road use, FMVSS301 should apply.

Principled fuel containment crashworthiness designs anticipate exposures beyond performance requirements in a minimum standard. Among the documents from the SAE Handbook, an approach to the design of fuel system crashworthiness was contained in the SAE Information Report for Passenger Car and Light Truck Fuel Containment [22]. The Information Report provided a structure of collision damage principles and underlying containment integrity guidelines. The containment integrity guidelines outline three major groups of failure mechanism - rupture, fill pipe or other component separation, and puncture. In the author's opinion, while much of the discussion of fuel system crashworthiness related to on-road crashes, the exposure, design concerns, and potential for mitigating crash induced fuel leakage is also applicable off-road.

For the sampled ROVs it was observed that known and effective crashworthy concepts and features were not always present. Based on the sample, the following crashworthiness features could be considered for ROV fuel system design:

- Tank designs and materials should anticipate intrusion and crush, including the element of fuel tank vapor space.
- Because of the observed fuel tank location, special guarding, shielding and other design features may be appropriate in anticipation of impact deformations and penetrations.
- Locating a fuel tank and its components away from zones of anticipated crush and penetration reduces exposure to crash induced failures.
- The location of the filler pipe and fuel cap was in one case partially outside of a protective structure. Fuel caps should be recessed or guarded and should have crashworthy features including the ability for the cap handle to sustain impact, deform or break away leaving the sealing components intact.
- The fill pipes were often ridged with no designed-in capability to accommodate impact deformations or penetrations. Because the filler pipe often transfers fuel from the side of the ROV where impact by rollover or collision is anticipated, features that enhance the capability of the fill end of the pipe to deform relative to the tank end without fracture or leakage should be provided. One-way valves on fill pipes should be considered.
- One example of a short vent line would have readily permitted fuel leakage in a sideward, pitched or inverted orientation. Vent systems should prohibit leakage in all roll or pitch orientations.
- Fuel and vent lines should anticipate deformations and connect by secured or clamped fittings. In cases of line failures, flow should be mitigated. Fuel pumps should not operate when the engine is stopped or after crash incidents.
- In anticipation of impact deformations and penetrations there were numerous examples of sharp objects in the environment of the fuel tanks. If the sharp objects cannot be eliminated then a shield of the tank or the sharp object should be provided. Mitigating the shape or size of a sharp object should also be considered.

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APPENDIX

APPENDIX A SAE GROUND VEHICLE STANDARDS, RECOMMENDED PRACTICES AND INFORMATION REPORTS

Review of SAE Standards, Recommended Practices and Information Reports relative to ROV fuel system crashworthiness attempted to identify specific provisions and exact language that related to fuel system crashworthiness. In some cases the provisions of an SAE document did not specifically state that its purpose was for crashworthiness, but a judgment was made by the author that the provision would result in a feature that affected crashworthiness.

SAE J2045, PERSONAL WATERCRAFT FUEL SYSTEMS

SAE J2045, Personal Watercraft Fuel Systems, was a Surface Vehicle Recommended Practice and an American National Standard [16]. Personal Watercraft - means a vessel less than 4 m in length, which uses an internal combustion engine powering a water jet pump as its primary source of propulsion, and is designed to be operated by a person or persons sitting, standing, or kneeling on, rather than within, the confines of a hull. The document specified guidelines for fuel systems of personal watercraft. Applicable requirements included:

- The fuel system shall be designed not to leak liquid fuel into the watercraft when: (a) the watercraft is overturned through 180 degrees of roll in either direction, and (b) the watercraft is overturned through 90 degrees of pitch in either direction (General, 4.2).

- The fuel system shall be designed to automatically stop the supply of fuel to the engine when the engine is not running (General, 4.4). And, only operate the fuel pump when engine is running or starting (Fuel Pumps, 8.2)

- Each fuel tank shall not support a deck, bulkhead, or other structural component (Fuel Tank Installations, 6.1).

- Fuel tanks shall not be integral with the hull or engine (Fuel Tank Installations, 6.2).

- Cellular plastic shall not be the sole support for a metallic fuel tank (Fuel Tank Installations, 6.5).

- Each hose in the tank fill system shall be secured to a pipe, spud, or hose fitting by a method which prevents leaks and prevents the hose from becoming disconnected (Fuel Tank Fill System, 7.2).

- Each fuel filter and strainer must be supported on the engine or boat structure independent from its fuel line connections, unless the fuel filter or strainer is inside a fuel system component (Fuel Filters and Strainers, 11).

- Except when used for a tank fill line, each spud, pipe, or hose fitting used with hose clamps shall have a bead, a flare, or a series of annular grooves or serrations no less than 0.4 mm (0.015 in) in depth (Spud, Pipe and Hose Fitting, 12).

- Hose clamps, when used, shall be beyond the bead or flare, or over the serrations of the mating spud, pipe, or hose fitting (Clips, Straps, and Hose Clamps, 13.3).

- Each vent and fuel distribution hose shall be secured by a method which prevents leaks and prevents the hose from becoming disconnected (Hoses and Connections, 16).

SAE J1241, FUEL AND LUBRICANT TANKS FOR MOTORCYCLES

SAE J1241, Fuel and Lubricant Tanks for Motorcycles, was a Surface Vehicle Recommended Practice and was submitted for recognition as an American National Standard [17]. The SAE Recommended Practice was applicable to two- or three-wheel motorcycles intended for highway use. Unless noted, requirements applied to both metallic and nonmetallic tanks. Accessory or aftermarket tanks as well as original equipment tanks were covered. Test procedures and performance criteria were established for the integrity of tanks, associated fittings, filler caps, and plumbing separate from the engine and transmission, used to supply fuel or engine lubricant to a motorcycle. Applicable sections included:

- All fuel tank filler caps should present a smooth contour, or shall be covered by a rear hinged access cover that presents such a contour. Hinged fuel tank filler caps shall be hinged at the rear (Design and Construction, General, 4.1.5).

- All hoses shall meet the applicable performance requirements of SAE J30 DEC93 or ISO 4639-1 (Design and Construction, General, 4.1.6).

- Cap Leakage Test - Rotate the tank about its longitudinal axis to positions 90 degrees, 180 degrees (inverted), and 270 degrees from the normally installed position and allow to stand for 5 min at each position (Cap Leakage Test, 5.6.3).
- Longitudinal Deceleration Test - The purpose of this test is to ensure the integrity of the fuel system in frontal impacts. The test involves installing the tank on a test platform and decelerating the combined test platform and the tank from a specified velocity to rest using a decelerator with specified force/deflection characteristics (Impact/Deceleration Tests, Longitudinal Deceleration Test, General, 5.8.4.1).
- Lateral Impact Test - The purpose of this test is to examine the integrity of the fuel system in lateral impacts. The test involves mounting the tank on a fixed test platform and impacting the side of the tank with a pendulum of specified shape and kinetic energy (Impact/Deceleration Tests, Lateral Impact Test, General, 5.8.5.1).
- Failure Criteria for the Cap Leakage Test, Longitudinal deceleration and lateral impact test was identical and included:
    - Failure of the fuel filler cap to remain closed (5.8.4.5.1).
    - Cracking, splitting, seam separation, or other tank damage resulting in external leakage in excess of 30 cc/min (1 fl oz/min). Immediate discharge of liquid from the pressure relief mechanism shall not constitute failure if it does not continue for more than 30 s (5.8.4.5.2).
    - Failure of the fuel line(s) to remain intact and properly attached to both the tank and the fuel delivery System (5.8.4.5.3).
    - Failure of the tank attachment fittings resulting in complete detachment of the tank from the test platform during the test (5.8.4.5.4).
    - Detachment of the tank from the test platform when the platform is rotated 360 degrees about the tank longitudinal axis after impact testing (5.8.4.5.5).

SAE J2358, LOW SPEED VEHICLES

SAE J2358, Low Speed Vehicles, was a SAE Surface Vehicle Standard [18]. This SAE Standard defines the safety and performance requirements for Low Speed Vehicles ("LSV"). The safety specifications in this document applied to any powered vehicle with: a minimum of 4-wheels; a maximum level ground speed of more than 32 km/h (20 mph) but less than 40 km/h (25 mph); a maximum rated capacity of 500 kg (1100 lb); and a maximum gross vehicle weight of 1135 Kg (2500 lb); that was intended for transporting not more than four (4) persons and operating on designated roadways where permitted by law. Personal Neighborhood Vehicles (PNVs) have the same general specifications as LSVs, but the maximum level ground speed is limited to 32 km/h (20 mph). Applicable requirements included:

- Flexible tubing or vibration loops shall be used where necessary (Fuel Systems, 8.3.1.2).
- The Fuel System Components shall be located, routed and contained within the vehicle in such a manner as to provide adequate clearance to heat generating components and damage from obstacles or projections that the vehicle may encounter during normal operation. "Adequate clearance" defines clearance necessary to avoid breakdown due to heat from heat generating components or abrasive elements (Fuel Systems, 8.3.2.2).
- Test - The tank shall be positioned upside down to allow the fuel cap to be at the lowest point of the fuel tank (Fuel Systems, Venting, 8.3.3.2). Test Acceptance - The fuel tank and its components, fill pipe, fuel gauge outlet, air intake vent, safety vent, and any other openings shall not spill or leak fluid at a rate greater than 30 mL (1 fluid ounce) in ten (10) minutes (8.3.3.3).

SAE J703, FUEL SYSTEMS - TRUCK AND TRUCK TRACTORS

SAE J703, Fuel Systems - Truck and Truck Tractors, was a Surface Vehicle Recommended Practice [19] that applied to systems for containing and supplying fuel for the operation of motor vehicles or for the operation of auxiliary equipment installed on, or used in connection with, commercial motor vehicles. A "side-mounted" fuel tank was defined as a liquid fuel tank which if mounted on a truck tractor, extends outboard of the vehicle frame and outside of the plan view of the cab (3.2.1); or if mounted on a truck, extends outboard of a line parallel to the longitudinal centerline of the truck and tangent to the outboard side of a front tire in a straight ahead position (3.2.2). In determining whether a fuel tank on a truck or truck tractor is side mounted, the fill pipe is not considered a part of the tank. SAE J703 was first issued in October of 1954, was removed from the SAE Handbook in 1980 and was reintroduced in December 2000. According to its Forward, the intent of the document was "not only to clarify the procedures and reflect the best currently known practices, but also to prescribe requirements in Sections 3 and 4 that meet or exceed all the corresponding performance requirements of FMCSR [Federal Motor Carriers Safety Regulations] 393.65 and 393.67 that were in effect at the time of issue." Applicable sections include:

- No part of the system extends beyond the widest part of the vehicle (Location, 4.2.1);
- No part of a fuel tank is forward of the front axle of a power unit (Location, 4.2.2);
- Fill pipe openings are located outside the vehicle's passenger compartment and its cargo compartment (Location, 4.2.4);
- A fuel line does not extend between a towed vehicle and the vehicle that is towing it while the combination of vehicles is in motion (Location, 4.2.5);
- No part of the fuel system is located within or above the passenger compartment (Location, 4.2.6);
- Each fuel tank must be securely attached to the motor vehicle (Fuel Tank Installation, 4.3);
- A fuel system must not supply fuel by gravity or siphon feed directly to the carburetor or injector (Gravity or Siphon Feed Prohibited, 4.4);
- Any portion of a fuel line which extends more than 50 mm (2 in) below the fuel tank or its sump shall be enclosed in a protective housing. Diesel fuel cross-over, return, and withdrawal lines which extend below the bottom of the tank or sump must be protected to minimize damage from impact (Fuel Lines, 4.6). Every fuel line must be: (4.6.1) long enough and flexible enough to accommodate normal movements of the parts to which it is attached without incurring damage; and (4.6.2) secured to minimize chafing, kinking, or other causes of mechanical damage (4.6.2);
- Joints of a liquid fuel tank must be closed by techniques that provide heat resistance equivalent to the parent materials and mechanical securement equivalent to 80% of the parent material. Joints include all the head and body seams and nonremovable adapters affixed to the liquid fuel tank (Construction of Liquid Fuel Tanks, 5.2.1);
- If there is a bottom fitting installed, it must not extend more than 19 mm (0.75 in) below the lowest part of the liquid fuel tank or sump (Bottom Fittings, 5.2.4);
- Tank Assembly Leak Test Procedure: Fill the fuel tank to 95% of its liquid fill capacity with the fuel it is designed to carry or an equivalent fluid. If the tester deems this procedure too hazardous, Stoddard solvent may be substituted. The test fluid must be between 10 and 27 °C (50 and 80 °F). Install the fill cap, air vent, and turn the tank through any angle in any direction about any axis from its normal installed attitude. As a second part of the previous test, turn the tank 90 degrees around its longitudinal axis as it may be mounted on a vehicle, introduce air at 28 kPa (4 lb/in2) and while it is pressurized, continue rotation about the same axis to 180 degrees (Tank Assembly Leak Test, 5.3.2.1);
- Air Vent Leak Test Procedure: Mount the air vent on an open container. Orient the container so that the vent axis is at any angle from upright to inverted. Introduce fuel the vent is designed to contain or an equivalent fluid into the container. Stoddard solvent may be substituted. While the vent is fixed in orientation, raise the liquid level in the container at a rate of not more than 0.6 cm (1.5 in) per second until the vent is fully submerged (Air Vent Leak Test, 5.3.3.1).
- Drop Test Procedure: Fill the tank with a quantity of water having a weight equal to the weight of the maximum fuel load of the tank and drop the tank 9.1 m (30 ft) on to an unyielding surface so that it lands squarely on an exposed outboard corner. In the case of a rectangular tank, the outboard corner is defined as one of the four corners farthest distant from the vehicle frame from which the tank is mounted. The corner of a round tank is defined as a point along the circumferential edge of the tank (Drop Test, 5.3.4.1).
- Fill Pipe Test Procedure: Fill the tank with a quantity of water having a weight equal to the weight of the maximum fuel load of the tank and drop the tank 3.1 m (10 ft) onto an unyielding surface so that it lands squarely on its fill pipe. The attitude of the tank in this test should be such that a longitudinal axis passing through the center of the fill cap and through the center of the intersection of the fill pipe and the tank is perpendicular to the impact surface (Fill Pipe Test, 5.3.5.1).
- The required performance for each test procedure was: "The liquid fuel tank assembly may not leak more than a total of 28.0 g (1 oz) by weight of water per minute."

SAE J288, SNOWMOBILE FUEL TANKS

SAE J288, Snowmobile Fuel Tanks, was a Surface Vehicle Recommended Practice [20] that provided minimum performance requirements for non-pressurized fuel tanks used on snowmobiles. Applicable requirements included:

- The tank shall remain functional in a temperature range of −40 to +60 °C when tested in accordance with Section 4 (Requirements, 3.1);

- Drop Test − Ensure that the fittings and caps are tightly installed. Drop the surface of the tank which is supported in the snowmobile immediately onto a hard smooth surface from a height of 1.25 m. Tanks attached by fasteners through integral bosses to mounting points on the snowmobile should be mounted in a fixture duplicating the mounting (Impact Test, 4.3.3). The acceptance criterion for the test was no leaks (Acceptance, 4.3.6) This test is conducted in two conditions: after condition in a cold chamber, −40 C, and a hot chamber, 60 C.

SAE J2587, OPTIMIZED FUEL TANK SENDER CLOSURE

SAE J2587, Optimized Fuel Tank Sender Closure, was a Surface Vehicle Recommended Practice that described performance requirements of fuel tank closures used in conjunction with fuel level senders and fuel delivery systems [21]. It provided guidelines that assure interchangeability and compatibility between fuel tanks and fuel pump/sender closure systems without specifying a specific closure system design. These systems may be used in rigid fuel tank systems made of plastic or metal.

Section 5 of the Recommended Practice was titled, Tests to Assess Robustness Against Vehicle Impact Events, and states:

"During vehicle impact tests, the fuel tank can be subjected to a number of different force mechanisms that have the potential to cause the sender closure system to leak or break. The circumstances that might result in leakage from the sender closure during or after a vehicle impact are dependent on many aspects of the total design such as:

- The tank design itself
- The relative placement of the sender closure within the envelope of the tank
- The design of the vehicle structure surrounding the tank
- The mean by which the tank is retained within the vehicle
- The presence or absence of shields
- The manner in which in-tank components are attached to the closure
- Etc.

It is the responsibility of the vehicle OEM to assess all aspects of the fuel tank and vehicle design to assure the integrity of the fuel system in the event of reasonably severe vehicle impacts."

SAE J1664, PASSENGER CAR AND LIGHT TRUCK FUEL CONTAINMENT

SAE J1664, Passenger Car and Light Truck Fuel Containment [22], was a Surface Vehicle Information Report. The Information report applied to liquid fuel containment system for gasoline or flexible fuels (up to 85% methanol in gasoline), along with their associated vapors, as designed for use on passenger cars and light trucks. The document addressed the fuel tank and components that were directly attached to the fuel tank, including: the filler neck, tank, fill vent tube, fuel cap, pump-sender, and rollover control valve closure seals, insofar as they act as closure or containment mechanisms. Mounting and shielding of the "system" components were included to the extent they affect containment. The Information report was issued in January 1994 and cancelled in March 2002. Applicable provisions included:

- In addition to meeting government standards, consideration should be given to all reasonably likely "real world" causes of fuel containment failure including reasonably foreseeable crashes, long-term corrosion effects, and other abnormalities such as failure of other vehicle components, assembly or service errors, and failures or abnormalities on other vehicles which might be involved in a crash (Failure Mode and Effects Analysis (FMEA) (Forward, b. (1));

- It would not be reasonable or practical to design fuel containment systems that would completely eliminate all risks of failure in any condition identified in a FMEA study; however, a disciplined FMEA approach can eliminate many "real world" failure modes and reduce the frequency of many others (Forward, b. (2));

- An automotive vehicle and its fuel containment system are subject to collision damage in an infinite variety of situations including various angles, speeds, and fixed or moving objects impacted, multiple impacts, and rollovers with or without preceding or subsequent impacts. A FMEA should be performed and consideration given to vehicle package and fuel containment system design in order to eliminate or minimize collision-related fuel spillage to the extent practicable (Collision Damage Principle, 3.3);

- Under crash event per FMVSS 301 or other reasonable crash circumstance, there should be no component rupture, puncture, or closure element separation from the fuel tank. It is suggested the engineer test design sensitivity to a variety of reasonable crash circumstances (Containment Integrity Guidelines, 4.14);
- Most importantly, fuel containment components should be packaged in a “friendly” environment. Material selection should consider puncture resistance, material thickness requirements, and burst pressure strength. Laminate or composite materials may have useful application, especially in providing a “shielding” function (General Design Considerations To Prevent Fuel Loss In Reasonably Severe Crashes, 4.14.1);
- Key causes of fuel loss during or immediately after a crash (4.14.2):
  - Hydrodynamic Rupture - In selecting the fuel tank placement in the vehicle, the engineer must consider vehicle structural collapse insofar as such collapse may affect the hydrodynamic rupture characteristics of the tank. It might be necessary in a given location to strengthen the structure surrounding the tank to prevent or limit the amount of tank deformation in a specific crash mode. Other factors to consider are:
    - Shape of tank.
    - Vapor space when tank is filled to design maximum (allowing for fuel expansion with temperature-the larger the amount of vapor space versus liquid fuel, the greater the ability of the tank to withstand crush).
    - Material properties (e.g., tensile strength, ductility, including visco-elasticity, if present, and impact strength). (A ductile material will absorb more energy.)
  - Filler neck or other component separation from tank. Key elements to consider are:
    - Joint structural properties to resist leaking from twist, bending, or axial loads, or combinations of these.
    - Relative separation or crush loads experienced during a crash. The filler pipe and its attachments to the tank and the outer body at the filler inlet should be designed to prevent, to the extent possible, separating the pipe from the tank. For example, the pipe to body separation force should be significantly less than the pipe to tank separation force.
    - Fuel caps are often subjected to prying forces and direct impact during crashes. Reasonable design efforts are suggested with the objective of maintaining system integrity when fuel caps are subjected to these loading mechanisms.
  - Puncture - Basically, the fuel tank should be protected from intrusion by other components. Emphasis should be placed on the following considerations with respect to overall crash integrity:
    - Shielding and shield shape when it contacts the fuel tank in a crash.
    - Tank material and thickness.
    - Location of “unfriendly” surfaces/components (and the path they travel during a crash).
    - Vehicle structural collapse characteristics in relation to the fuel tank location (considering the variety of impact directions) as well as to other fuel containment components (e.g., fill neck).
    - Penetration by a striking object external to the vehicle.

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