# RESEARCH TO EVALUATE SAFETY TECHNOLOGIES FOR VULNERABLE FUEL TANKS

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## ABSTRACT

In 1993, the U S Department of Transportation ordered a recall of approximately 5,000,000 GM pickup trucks equipped with sidesaddle fuel tanks due to their alleged vulnerability in severe side crashes. The fuel tanks on these pickups were located under the cab and bed outside the frame rails. The recall was subsequently rescinded in favor of an administrative settlement.

Prior to the settlement, NHTSA conducted a research program that included more than twenty crash tests. NHTSA defined a crash configuration that the pickups with sidesaddle tanks failed but competitive models of trucks passed. The test involved an 80 km/h (50 mph) side impact by a Chevrolet Caprice, in a breaking attitude, aligned so that it impacted the fuel tank at an angle of 30 degrees. In 1999, a follow-on project was undertaken by the Automotive Safety Research Institute (ASRI) to evaluate alternative tank systems to the sidesaddle design. The alternatives investigated included the following: providing a cage for tank protection, incorporating a fuel bladder, changing tank materials, and relocation of the tank. In conjunction with these design alternatives a number of other technologies were investigated, such as, shielding of fuel lines, check valves, self-sealing break away fuel line couplings, and fire suppressant panels.

Eighteen full-scale crash tests were conducted to evaluate the various technologies. The best test results were obtained by two strategies that moved the tank to less vulnerable locations. Tests of strategies that attempted to maintain the tank in its sidesaddle location were not successful. Break-away couplings in the fuel lines, a flapper valve in the filler tube and shielding of vulnerable fuel lines were tested under conditions that demonstrated their efficacy. Other technologies showed promise but were not fully developed and tested.

## INTRODUCTION

In 1967 the National Highway Traffic Safety Administration (NHTSA) introduced the Federal Motor Vehicle Safety Standard (FMVSS) No. 301, "Fuel System Integrity" [NHTSA Part 571.301] to reduce deaths and injuries occurring from fires. Initially, the standard only applied to passenger cars. However, in 1977 light trucks were also included. The standard prescribes three full-scale tests, a frontal, rear and lateral impact, following which a maximum acceptable fuel leakage rate is specified. After the crash test, the vehicle is subjected to a 360$^o$ roll, during which fuel leakage must be below specified levels. The frontal impact comprises directing the subject vehicle into a flat-face, rigid barrier at a speed of 48.0 km/h (30.0 mph). For both the rear and lateral test, an 1814 kg rigid-flat-faced, moving barrier impacts the stationary vehicle. The test speed is 48.0 km/h (30.0 mph) for rear impacts and 32.0 km/h (20.0 mph) for side impacts. In each test configuration the fuel tank must be filled to 90% to 95% capacity.

The General Motors C/K full size (10 to 30 series) pickup model years spanning 1973 to 1987, employed a sidesaddle tank design in which the tank was mounted outside the vehicle's frame rails. This design was alleged by the Department of Transportation to represent a safety related defect in that the tank placement exposed the tank to more severe damage during a side impact collision compared to vehicle designs in which the fuel tank is inside the frame rails. Although the sidesaddle design was largely discontinued in the 1988 and later models, it persisted on a few configurations until 1991.

In December 1992, the NHTSA Office of Defects Investigation (ODI) opened an investigation to determine if certain 1970-1991 Chevrolet C/K pickups contained a safety related defect [ODI, 1994]. The ODI investigation was to determine whether these full size pickups posed an unreasonable risk to safety, related to the danger of fires following crashes, with primary focus on side impact crashes. Based on ODI testing and full-scale test data provided by GM, it was concluded that the C/K trucks, to which the 301 Standard applied, were in compliance. The ODI's analysis of 1979-1993 real-world accident data suggested that the incident of fatal crashes involving fire was nominally 2.5 times higher for the C/K pickup trucks over that of its competitors. However, the ODI concluded that fatal side-impact crashes involving fire were generally more severe than the crashes specified by the FMVSS 301 standard. Crash testing disclosed that the C/K pick fuel system exceeded the leakage requirements of the 301 standard when impacted in the side by a Chevrolet Caprice traveling at 80 km/h (50 mph). Competitive pickup models were found to survive this test. Test dummies in the crashed vehicles indicated that the 80 km/h (50 mph) side impact by a Caprice did not produce excessive injury measures.

On April 9, 1993, ODI recommended to General Motors a safety recall on GM pickup models with the tank mounted outside the frame rails [ODI, 1994]. Subsequent negotiation between GM and the Department of Transportation resulted in an administrative settlement in lieu of a recall. Under this March 7, 1995 settlement, GM agreed to expend $51.355 million to improve vehicle and highway safety [NHTSA, 2001]. The settlement included $10 million for research to improve fire safety of motor vehicles. In a subsequent judicial settlement, dated June 27, 1996 GM agreed to provide an additional $4.1 million for motor vehicle fire safety research [Judicial District Court, 1996]. In the same settlement, the Class Plaintiffs' agreed to provide $1 million for the design, development, testing, and implementation of fuel system safety enhancements for the C/K trucks. This latter project has been administered by the Automotive Safety Research Institute and is the basis for this paper.

In September 1999, The Automotive Safety Research Institute (ASRI) initiated a research project to investigate possible alternatives to the existing sidesaddle fuel tank design that would improve the pickup truck's fuel tank crashworthiness under side impact loading conditions. To this end, Biokinetics and Associates Ltd. was contracted to identify, retrofit and test alternative fuel tank systems or tank protective strategies for the C/K pickup trucks. A preliminary review of the existing tank designs and readily available technologies identified six possibilities, which included:

1. Replacing the sidesaddle tank with a bed-mounted tank system.
2. Installing a custom fabricated tank inside of the vehicle's frame forward of the rear axle.
3. Replacing the sidesaddle tank with an auto racing fuel cell.
4. Replacing the existing sidesaddle steel tank with a plastic tank designed specifically for the C/K trucks.
5. Adding a protective frame around the existing sidesaddle tank.
6. Installing a custom fabricated tank inside of the vehicle's frame behind the rear axle.

All six alternatives were installed in 1985 to 1987 C/K pickup trucks and subjected to the critical test condition for the sidesaddle tanks. The critical test condition was an 80 km/h (50 mph) side impact by a Chevrolet Caprice. Based on the favorable results obtained, the center-mounted tank and the bed-mounted tank were selected for further development and testing in other impact modes. Although the tank mounted behind the axle passed the critical test for sidesaddle tanks, it was not tested further due to its vulnerability to side and rear impacts directed at its location.

## TEST CONFIGURATION

The crash worthiness of the selected tank systems was evaluated under various full-scale crash configurations. The pickup trucks used in the test were 1985 through 1987 two-wheel drive Chevrolet or GMC ½ or ¾ ton pickups. One four-wheel drive pickup was tested. For the side impacts, the bullet vehicle was either a Chevrolet Caprice or a FMVSS 301 moving barrier. The impact speed was nominally 80.0 km/h (50 mph) for the Caprice and 64.0 km/h 40 mph) for the barrier. For the Caprice, the angle of impact was 60$^o$ from the front of the truck and inline with a point on the truck's centerline located between the cab and the truck bed. For the FMVSS 301 rigid moving barrier, the impact was perpendicular to the longitudinal axis of the truck and centered on the space between the truck bed and the cab. The typical set-up for the side impact Caprice tests and the moving barrier side impact test are shown in Figure 1 and Figure 2.

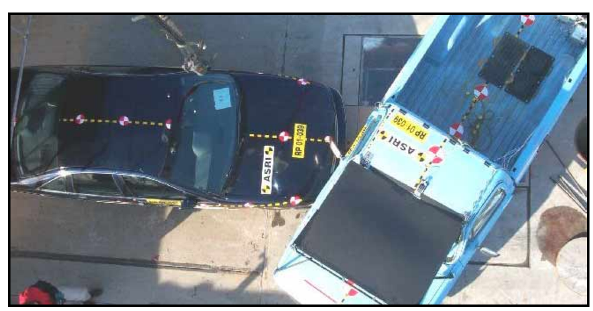


**Figure 1. Typical vehicle alignment in side impact tests with a Caprice as the bullet vehicle**

**Figure 2. Alignment of the FMVSS 301 barrier for side collision**

Tests conducted with the Chevrolet Caprice as the bullet vehicle replicated as far as possible the critical vehicle to truck configurations used by the ODI during its investigation into the sidesaddle fuel tanks. This baseline test was conducted at the Vehicle Research and Test Center (VRTC) and the vehicle set-up and the test parameters were documented in Transportation Research Center Inc.'s (TRC) test report No. 930324 [Markusic, 1993].

The ride height of the bullet vehicles was adjusted to compensate for braking. VRTC had determined that under heavy braking the front of the vehicle lowered by 73.7 mm as measured from the front bumper centerline and the rear of the vehicle raised up by 63.5 mm as measured from the centerline of the rear bumper. To achieve this braking attitude a level ride was first established and then the front and rear axles were loaded and unloaded respectively to correspond to the pre-test attitude reported in TRC's Report 930324.

Frontal and rear impact barrier tests were also performed following test procedures similar to those specified in the FMVSS 301 safety standard with the exception of impact speeds that at times were elevated from those specified in the standard. The three frontal barrier tests consisted of a truck colliding perpendicularly into a rigid immovable flat wall. The first of these three tests was performed as per the letter of the FMVSS 301 standard with an impact speed of 49.0 km/h (30.6 mph). The second and third frontal tests were performed at an elevated nominal speed of 51.8 km/h (32.4 mph). Similarly, two rear barrier tests were performed with a stationary truck being struck from the rear by a moving FMVSS 301 rigid barrier at speeds of 49.0 km/h (30.6 mph) and 56.2 km/h (35.1 mph) respectively.

**PASS/FAIL ASSESSMENT**

A tank system that complied with the leakage requirements specified in the FMVSS 301 standard was considered to have passed the crash test. If the post crash fuel leakage was within the specified limits, the integrity of the tank was further verified, as per the standard, by inverting the entire truck about the longitudinal axis in increments of $90^o$. The presence of leaks was again compared to the leakage limits specified in the FMVSS 301 rollover requirement. The magnitude of the allowable leakage is about 1 oz. per minute.

Most of the tests performed were research oriented and did not comply with all the procedures set forth in the FMVSS 301 standard. For example, either the collision speed or the selection of the bullet vehicle varied from that specified. Consequently, compliance with the leakage requirements alone did not infer compliance with the standard. Ultimately, tests were conducted in all crash directions required by FMVSS 301, but were at higher crash severities than specified by the standard.

**THE BED-MOUNTED TANK**

The ODI study had concluded that the fuel tank located in the sidesaddle position results in increased risk of fuel leakage in side impact crashes. One objective of the tank relocation strategy was to install the tank in a position in which it would be less susceptible to direct loading from an impacting vehicle. By mounting a tank system in the bed of the truck, it would be both higher than typical bumper and frame heights on most vehicles and it would gain additional clearance from the side of the truck, effectively removing the tank from direct loading and avoiding undue damage. Additionally, the structure of the cab and of the bed itself would add to the protection afforded to such a system. However, such an installation reduces the capacity of the bed and limits some of its functions.

A bed-mounted tank system was installed behind the truck cab in seven GM pickup trucks. A secondary tank system was also installed on six of these trucks. The secondary tank system consisted of a custom fabricated tank installed in between the frame rails. A fuel line switching valve was installed for each truck with a secondary tank such that the truck could function from either system.

The bed-mounted system consisted of relocating a standard OEM steel tank and brackets, normally installed in the sidesaddle position, into the bed of the truck. Standard mounting brackets were used with additional holes drilled in the brackets such that they could be bolted vertically into the floor of the truck bed. A typical installation is shown in Figure 3.

**Figure 3. OEM bed tank installation with OEM brackets**

The tank was covered by a 3 mm thick aluminum checker plate shield for protection from shifting cargo. The shield installation is shown in Figure 4. The shield weighed 15.8 kg and cost approximately $215. Other miscellaneous hardware required for the bed installation cost $40. The installation time for the bed tank and shield was 3 hours. Installation procedures for this tank were documented in a report [Fournier et al, January, 15 2003].

**Figure 4. Typical in-bed installation of an OEM tank with shield**

In some tests the tank was left exposed so that it would be visible from overhead camera views.

Eight of the tested tank systems consisted of relocating a sidesaddle tank into the bed of the truck. The results of all the bed-mounted tank tests were summarized in a report [Fournier February 2002] that lists the tests and shows the results.

The side impact test with the Chevrolet Caprice as the bullet vehicle, as shown in Figure 1 did not challenge the tank in the bed location. The pickup damage was located below the bed of the truck, and the tank was well protected. To provide a more challenging test, an FMVSS 301 rigid faced moving barrier was used, as shown in Figure 2. However, the barrier speed was increased from 32 km/h (20 mph) to 64 km/h (40 mph). The bed-mounted tank passed this test.

**Table 1.**

**Summary of Bed-mounted Tank Test Results**

| Test No. | Test Type | Speed (km/h) | Results |
|---|---|---|---|
| RP01-036 | $60^{O}$ lateral impact Caprice | 81.4 | Pass |
| RP01-037 | $90^{O}$ lateral 301 barrier | 64.2 | Pass |
| RP02-028 | frontal barrier | 49.0 | Pass |
| RP02-029 | rear impact 301 barrier | 49.0 | Pass |
| RP02-031 | rear impact 301 barrier | 56.2 | Pass |
| RP02-032 | Frontal barrier | 51.8 | Pass |
| 20010462 | Handling test | Na | OK |
| 011024 | Dynamic rollover test | 50.2 | Pass |

Two frontal and two rear impact barrier tests were also performed following test procedures similar to those specified in the FMVSS 301 safety standard with the exception of impact speeds that at times were elevated from those specified. The two frontal barrier tests consisted of a truck colliding perpendicularly into a rigid immovable flat wall. Similarly, two rear impact tests were performed with a stationary truck being struck from the rear by a moving FMVSS 301 rigid barrier.

To verify that a truck's baseline stability and handling characteristics were not adversely affected, both a dynamic rollover test and a handling test were performed.

The rollover test was performed as per FMVSS 208. The truck was mounted on a cart at an angle of $23^{O}$ with the driver's side elevated such that the longitudinal axis of the truck was perpendicular to the direction of cart travel. The cart was accelerated down the test track and the truck was released and allowed to roll. The truck rolled four quarter turns. No leakage resulted from the rollover, or the subsequent static rollover performed in accordance with FMVSS 301.

An analysis of the expected vertical change in the position of a truck's CG and its influence on the Static Stability Factor (SSF) was performed. Baseline vehicle information was obtained from measurements recorded in the NHTSA's database on vehicle inertial parameters, which specified vehicle weights and the height of their CG above ground [Heydinger 1999]. Seven trucks from the database were included in the analysis, each of which had a filled sidesaddle tank installed. The cited values from the database were not corrected for the removal of the sidesaddle tank that would accompany the installation of the bed-mounted tank system.

The estimated change in the trucks' CG and SSF were calculated based on a bed-mounted tank system having a total mass of 91.0 kg, which includes the tank, brackets, shield and 76.0 liters of fuel. The SSF was calculated according to the following formula:

$$SSF = T/2H \qquad (1.)$$

Where,

T = vehicle track width
H = vehicle CG height

The static stability factor for the seven baseline trucks ranged from 1.12 to 1.25. The tank in bed filled with fuel reduced the factor by 0.7% to 1.4%. An equivalent or larger change in stability factor could result from normal loading of the pickup bed with cargo.

Handling tests were performed at the Transportation Research Center (TRC) in Ohio to investigate the effect of the increase in CG height from the installation of a bed-mounted tank. A pickup truck with a bed-mounted tank and outfitted with safety outriggers was subjected to a series of four abrupt driving maneuvers by an experienced test driver. The purpose of these maneuvers was to evaluate the effects of fuel sloshing on vehicle stability. The four handling maneuvers included: Double Lane Change, "J" Turn, Slalom and Resonant Steer.

Initially, an empty bed-mounted tank without baffles was evaluated to provide a baseline for comparative purposes. The tank was then filled to half its capacity and finally to full capacity. An additional test was performed with the tank filled to half capacity with the inclusion of internal tank baffling.

For each handling maneuver the driver provided subjective feedback with regards to variations in the trucks handling characteristics as they related to the various tank fill levels or the inclusion of tank baffling. The driver's feedback suggested that the differences in handling were minor and were likely related to the additional fluid mass and not to fluid movement. Additionally, the driver indicated that there was no difference in handling with the introduction of tank baffling.

The relocation of the OEM tank to the pickup bed was by far the simplest alternative to the sidesaddle tank installation. It is applicable to all models of GM C/K pickup trucks without modifications and it employs a readily available tank, sending unit, mounting brackets and requires minimal modifications to the truck or tank components. The modifications consist of drilled holes in the bed floor for securing the mounting brackets and for routing the fuel lines to the engine. Additional holes are also needed in the mounting brackets for securing a simple aluminum cover to protect the tank from shifting payloads. A limitation of the system, however, is that it reduces the utility of the bed by decreasing the availability of cargo space.

**CENTER-MOUNTED TANK**

The chassis of the C/K pickup trucks is basically a ladder type configuration. Two substantial longitudinal frame rails are tied together by cross members at various points along their length. By placing a tank in between these rails, a center-mounted tank system would gain protection by the rigid rails acting as a shield, diverting the load path from directly bearing on the tank. Additionally, the front end of the tank would gain extra protection from the structure of the cab and the truck bed.

The drive shaft and the exhaust system occupy the space between the frame rails. The drive shaft runs down the middle of the truck while the exhaust system is routed between the left frame rail and the drive shaft leaving the space between the right frame rail and the drive shaft available for installing a center-mounted tank.

Prior to 1982, C/K trucks were built with the fuel tank installed on the right side and with the fuel filler door located on the same side. In this configuration, connecting a center-mounted tank to the filler neck would require a fuel hose marginally longer than that used by the original fuel system. However, for later model years, 1982 to 1987, the fuel tank was relocated to the left side of the truck. To maintain a comparably short filler tube for the center tank, the exhaust system would have to be re-routed to the right side of the drive shaft, freeing the left side for the center tank. This was done for the first truck that was crash tested. However, this exhaust modification introduced a higher cost to the retrofit. Therefore, for the remaining trucks the center tank was installed on the right side, with the filler tube to be routed from the filler door located on the left side of the truck to the tank spout. The center-mounted tank and its associated supports are shown in Figure 5. Figure 6 and Figure 7 show the tank installed in a pickup.

**Figure 5. Center-mounted with mounting brackets**

**Figure 6. Typical center-mounted tank installation – Rear View**

**Figure 7. Typical center-mounted tank installation – Front View**

The design of the center-mounted tank and its associated mounting brackets evolved based on information gained during the test program, incorporating features to improve its crashworthiness.

The center-mounted tank was custom fabricated at a welding shop specializing in fuel tanks. It comprised a box shaped container fabricated from 1.52 mm thick sheet steel. This steel is thicker than that used in the original equipment manufacturer's (OEM) mass produced tanks, which were nominally 0.86 mm thick. The reasons for the thicker steel were two fold: first, the thicker steel simplified the manual welding process and second it offered improved resistance to damage. The tank was held in place at three locations. The front and center of the tank were strapped down to a substantial "L" shaped bracket that bolted directly to a frame rail and supported the tank from underneath (See Figure 6 and Figure 7). A strap that attached to the frame rail and a cross member supported the rear of the tank. The weight of the straps, brackets and miscellaneous components was 12.1 kg. Approximately three hours of labor was required to install the tank. . Installation procedures for the center-mounted tank were documented in a report [Fournier et al, January 29, 2003].

The fluid volume of the tank was 71.9 liters and its weight was 17.2 kg. The distance between the drive shaft and the frame limited the tank width. Drive shaft to tank clearance greater than that on model year 2000 GM pickups was maintained. Tank depth was limited by ground clearance requirements.

From the fourth test onwards, the tank was modified to include a 25.4 mm radius to the lower longitudinal edges of the tank. The purpose of the radius was to reduce localized stress resulting from folding a right angle edge in on itself when loaded. Additionally, the material for the middle bracket was changed from steel channel with right angle edges to steel tubing with rounded and thus less aggressive edges. Loading on the tank from these brackets would therefore be more evenly distributed, decreasing the possibility of tearing of the tank resulting from concentrated edge loading from the brackets.

During frontal impact testing it was discovered that the tank shifted forward excessively upon impact. Unlike the OEM steel tanks that are fabricated using a stamping process that can incorporate recesses for the mounting straps that aid in preventing sliding, the flat sides of the custom tanks allowed movement of the tank through the mounting brackets' straps. This deficiency was overcome by increasing the clamping pressure of the mounting straps and by adding a tank catch plate at the front. One end of the plate was bent down to hook onto the front tank support bracket, while at the other end; the plate was bent upwards to prevent the tank from undergoing excessive translation. This plate was sandwiched in place between the front bracket and the tank.

Various fuel tank components other than the tank itself were evaluated during different tests. They included a plastic shield under the tank, a filler tube check valve and an after market sending unit. The plastic shield provided additional protection to the bottom and both sides of the tank. However, the tank was also tested without the shield and performed satisfactorily. On many of the tanks tested a reverse flow check valve was installed. In the event that the fuel filler tube was severed or torn from the tank, the check valve would prevent excessive fuel spillage. The diameter of the check valve obtained for testing was smaller than the filler hose, which resulted in a flow restriction that increased the time needed to fill the tank. The functionality of these valves was never required, as the filler tube remained intact and connected to the tank during all of the tests.

Eleven full-scale crash tests on the GM C/K trucks were conducted at PMG Technologies' Test and Research Center in Blainville, Quebec, Canada. The sequence of tests and their configurations and the overall success of the tests are summarized in a report [Fournier et al, October 2001].

All of the tests involving the Chevrolet Caprice as the bullet vehicles were conducted under identical conditions. These tests duplicated the 80.0 km/h (50.0 mph) 60° tests conducted by NHTSA during their defects investigation program.

A characteristic of each Caprice test was that upon impact the truck was lifted off the ground and carried laterally a short distance before the truck tires came back in contact with the ground. Both vehicles continued moving before coming to rest, typically with the Caprice wedged under the side of the truck. In the initial test, the truck rolled one quarter turn after the impact. The fuel leakage following this dynamic rollover and the subsequent static rollover was less than permitted by FMVSS 301. This test demonstrated the integrity of the fuel system in both side impact and rollover. Subsequent tests incorporated anti-roll bars to prevent dynamic rollover after the impact.

The final tank design demonstrated the ability to withstand the 80.0 km/h (50 mph) Chevrolet Caprice side impact that had been the critical test condition for the OEM tank. In addition, the tank design was tested to and passed front, side and rear impacts more severe than required by FMVSS 301. The test results are summarized in Table 2.

**Table 2.**

**Summary of Center-mounted Tank Test Results**

| Test No. | Test Type | Speed (km/h) | Results | |
|---|---|---|---|---|
| | | | Tank | Lines |
| RP01-009 | 60° side impact by a Caprice | 81.6 | Pass | Pass |
| RP01-036 | 60° side impact by a Caprice | 81.4 | Pass | Fail (1) |
| RP 01-037 | 90° side impact by a 301 barrier | 64.2 | Pass | Pass |
| RP 01-038 | 60° side impact by a Caprice | 81.4 | Fail (2) | Fail (2) |
| RP 01-039 | 60° side impact by a Caprice | 81.4 | Pass | Pass |
| RP 02-028 | Frontal barrier | 49.0 | Pass | Pass |
| RP 02-029 | Rear 301 barrier | 49.0 | Pass | Pass |
| RP 02-030 | 60° side impact by a Caprice (4x4 truck) | 80.0 | Pass | Pass |
| RP 02-031 | Rear 301 barrier | 56.2 | Pass | Pass |
| RP 02-032 | Frontal rigid barrier | 51.8 | Fail(3) | Pass |
| RP 02-096 | Frontal rigid barrier | 51.8 | Pass | Pass |

(1)No tank leakage; fuel line switching valve crushed.
(2)Truck tested with manifold removed – reduced inherent protection. Induced tank and fuel line improvements.
(3)Transmission web caused stress concentration. Induced a tank improvement.

## AUTO RACING FUEL CELL

A fuel cell, designed for automotive racing applications, was installed in the sidesaddle location on two trucks. The fuel cell that is designed to be both resistant to impact and non-exploding is comprised of a rubberized fabric bladder inside a rigid outer container. The cost of the fuel cell was $1080. A report describes the fuel cells and the test results in detail [Fournier et al November 2002]. The test results are summarized in Table 3.

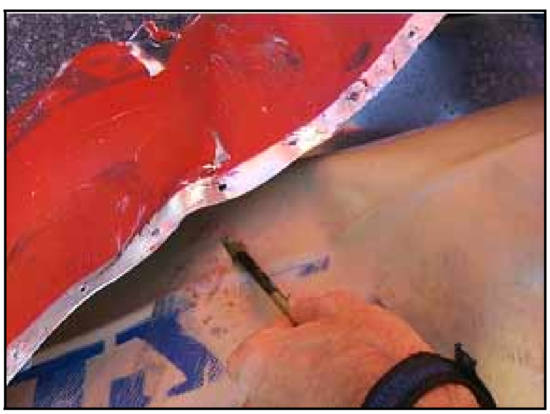
**Table 3.**

**Summary of Fuel Cell Tank Test Results**

| Test Nr. | Test Type | Speed (km/h) | Results |
|---|---|---|---|
| RP01-010 | $60^{O}$ lateral impact from a Caprice | 80.3 | Fail |
| 020821 | $60^{O}$ lateral impact from a Caprice | 80.5 | Fail |

In the first test, the outer container of the fuel cell consisted of a riveted aluminum enclosure held in place by two steel brackets that supported the tank from underneath. During impact, the outer casing ripped open from a combination of direct loading from the bullet vehicle and from hydrodynamic pressure from the expansion of the internal bladder that was compressed between the vehicle frame rail and the bumper of the bullet vehicle.

a)



b)

**Figure 8. Damage to the fuel cell aluminum housing (a) cut in fuel cell caused by sharp aluminum surface (b)**

With the aluminum container ruptured, the fuel cell inside was ejected from the truck. In the process, all the fuel lines connected to the tank were severed. The filler tube was disconnected from the tank, but a reverse flow flapper valve in the tank prevented spillage at the filler spud. Additionally, a rollover valve on the vent line prevented fuel leakage from the severed vent hose. There were no provisions in the fuel supply line to prevent fluid loss in the event that the line was severed and consequently it leaked fuel. However, the majority of fuel spillage stemmed from a tear in the bladder that was discovered along its lower inside edge. The damage was caused by the rear mounting bracket/strap that failed during the impact and perforated the aluminum outer housing creating sharp edges on the inside of the housing that cut or punctured the bladder. The damaged aluminum cover and fuel cell puncture are shown in Figure 8.

A second fuel cell system was assembled addressing the shortcomings identified by the results of the first test. Enhancements to the second fuel cell included fabricating the outer housing from steel rather than aluminum with through bolts instead of rivets to secure the hosing cover and the end plates of the container. The mounting brackets, which previously supported the tank from underneath, were replaced with brackets from which the tank was suspended. The intent of the new bracket arrangement was to allow the tank to deform without being restricted by the mounting brackets. To prevent fuel leakage from severed fuel lines, self-sealing breakaway connectors were installed on the fuel delivery and returns lines. As with the previous fuel cell, the vent line relied on an internal rollover valve.

Despite the enhancements to the outer container and the mounting system the tank bladder was again ejected during the impact. The bolts that fastened the outer container together pulled through the sheet steel and the outer container unraveled allowing the bladder to be ejected. The top cover of the container tore along the rear-mounting bracket adjacent to the bladder bulkhead, resulting in a sharp pointed corner that perforated the top surface of the bladder.

In the process of being ejected the breakaway connectors on the fuel and return lines disconnected as intended and no leakage resulted. The vent line was severed, but no leakage occurred due to the upright orientation of the tank. The vent line contained a rollover check valve located inside the tank. This valve was not exercised in the crash. The fuel cell laceration and the ruptured steel container are shown in Figure 9.

a)

b)

**Figure 9. Steel housing for bladder [arrows show ruptured seam (a)]; cut in top of fuel cell [arrow shows sealed break-away fuel coupling (b)]**

Fuel leakage was minimal following the crash although it was apparent that leakage from the puncture in the bladder would have been inevitable had the bladder been lying on its side rather than upright.

There are three grades of fuel cell bladders FT3, FT3.5 and FT5 offering increasing resistance to tearing and puncture. An FT3 bladder was used in both tests, therefore, by incorporating a higher rated bladder and by designing better protection for the bladder, it may be possible to improve its resistance to damage from direct exposure to slash or puncture hazards. Further research to improve the bladder was not initiated, because the alternatives for relocating the tank appeared to be more economical.

## TANK PROTECTION

An objective of the tank protection system was to redirect part of the load path from the tank to the vehicle's frame. Two such protective systems were tested and the results are summarized in a report [Fournier et al, January 2001]. Table 4 lists the tests conducted and the results.

**Table 4.**

**Summary of Tank Protection Test Results**

| Test No. | Test Type | Speed (km/h) | Results |
|---|---|---|---|
| RP01-008 | $60^{O}$ lateral impact from a Caprice | 81.1 | Fail |
| RP01-012 | $60^{O}$ lateral impact from a Caprice | 81.1 | Fail |

The first system consisted of the standard OEM tank, protected by a tank guard whose height off the ground was approximately the same as the bumper height of the bullet vehicle. The guard consisted of 76 mm angle iron, reinforced with tubular steel on its lower edge, protecting the lower outside edge of the tank. The angle iron was fastened to the vehicle frame at the front end of the fuel tank and to the frame and truck bed at the rear. Connection to the frame was via cantilevered tubular steel supports with resistance to downward bending provided by vertically fastening the rear tubular support to the truck bed. The total weight of the protective frame was 34.5 kg. Its cost was estimated at $120.

Notwithstanding the additional bracing of the rear support, neither the protective frame nor the vehicle structure to which it was bolted were capable of resisting the severe downward torque applied by the impacting vehicle, thereby, leaving the tank exposed and vulnerable to direct loading by the bullet vehicle. A significant tear in the tank resulted in excessive fluid loss. Damage to the tank and frame are shown in Figure 10.

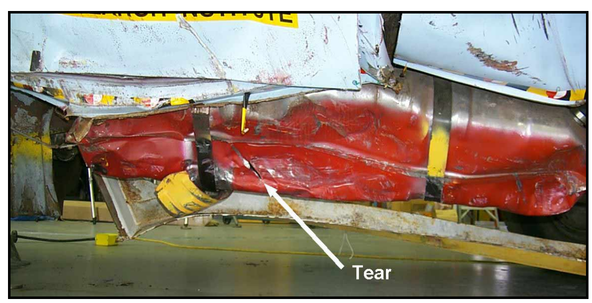



**Figure 10. Damage to the tank protective frame**

A retest of the tank protection system was performed with a second system based on the initial frame except with two additional attachment points to specifically counteract the downward moment applied by the impacting vehicle. The front end of the guard was fastened vertically to the cab floor and an additional support was added at approximately two thirds of the guard's length back from the front end that connected the guard vertically to the bed floor. These additional features increased the total weight of the tank protective frame to 46.7 kg.

The tank protective system remained attached to the vehicle frame during impact and, as intended, the additional vertical support of the guard prevented its downward displacement. The mounting brackets suffered comparatively minor bending with distortion of the guard's supports occurring primarily in the rearward direction.

A plastic tank was installed for the second test instead of a steel tank as used initially. Despite the improved performance of the protective frame, the guard compressed the tank cutting the top outside front corner of the tank resulting in excessive fuel leakage. The damage to the modified tank protective frame is shown in Figure 11. The damaged area of the tank was not exposed directly to the impacting vehicle. Rather, the damage was likely caused by the truck's structure which intruded into the tank space.

**Figure 11. Damage to the modified tank protective frame**

Development of the tank protection system was discontinued because the system performed poorly, and it was heavy and costly.

**PLASTIC TANK**

An aftermarket plastic tank costing $145 was purchased for evaluation. The plastic tank was used in two configurations. The first was as a direct replacement of the standard OEM steel tank. The second was also in the sidesaddle location with a tank protection frame in place. The tank protection design and test results of the two tests are contained in two reports [Keown, December, 1999 and Keown, September, 2000]. Test results are summarized in Table 5.

**Table 5.**

**Results of Two Tests with Plastic Tanks**

| Test No. | Test Type | Speed (km/h) | Results |
|---|---|---|---|
| RP01-011 | $60^{O}$ lateral impact from a Caprice | 81.3 | Fail |
| RP01-012 | $60^{O}$ lateral impact from a Caprice (Tank with Protection) | 81.1 | Fail |

Tears in the tank, as a result of excessive deformation, were only one of the failure modes. Punctures and cuts from aggressive components on the truck itself or on the bullet vehicle were also prevalent. Damage to the tanks is shown in Figure 12. The available aftermarket plastic tank did not offer any improvements over the existing OEM steel tank. Considerable additional development appeared necessary for significant improvements. This approach was discontinued.

**Figure 12. Puncture and slash damage to plastic tank**

**REAR MOUNTED TANK**

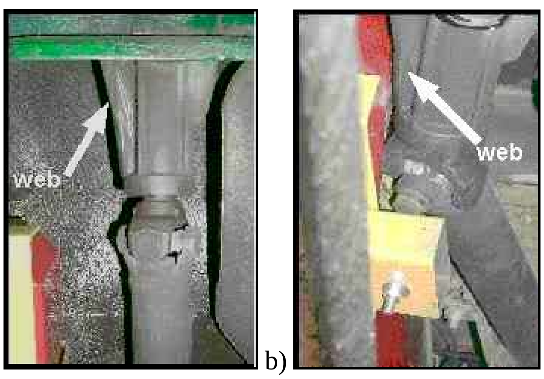
An aftermarket rear mounted tank was installed on one truck and subjected to the 80km/h (50 mph) Caprice test and it performed satisfactorily. However, due to its potential vulnerability to a Caprice test in a rear impact, this approach was not continued. The cost of the tank kit was $400. The configuration is shown in Figure 13.

**Figure 13. After market rear mounted tank**

## ADDITIONAL OBSERVATIONS

### Features to Address Hazards in the Center-Mounted Tank Location

Relocating the tank between the frame rails reduces its vulnerability to side impact, but may increase vulnerability in some other crashes. In severe crashes into a rigid frontal barrier the engine and transmission move rearward. An aggressive web on one of the alternative transmission produced a leak in one frontal barrier test. In addition, the drive shaft may buckle in the direction of the tank causing damage. Figure 14 shows the location of the aggressive transmission web and the drive shaft relative to the tank before and after a frontal crash test.




a) b)

**Pre-test** **Post-test**

**Figure 14. Drive shaft and transmission clearance in severe frontal crash – before (a) and after (b)**

The final center-mounted tank design addressed both of these undesirable loadings. The transmission contact was mitigated by increasing the tank to transmission clearance and by chamfering the corner of the tank to reduce the stress concentration when contact occurs. The drive shaft contact was addressed by maintaining OEM drive shaft clearance for center-mounted tanks and by positioning the tank brackets to resist drive shaft loading. The tank thickness of 1.52 mm. provided added protection compared with 0.86 mm. in the OEM tank.

### Protection of Fuel Lines and Fuel Selector Valve

The Caprice impact produced extensive deformation to the pickup frame. In some cases the fuel lines and/or fuel selector valves were severed by being pressed between the inside of the frame and the engine. This problem was aggravated in one test in which the exhaust manifold had been removed. In that test, the fuel line was severed when entrapped between the frame and a flange on the transmission. To improve the survivability of fuel lines, a structural shield was added inside the frame to protect the fuel filter. The shield is shown in Figure 15. No fuel line ruptures occurred on tests with the shielding in place.

**Figure 15. Shielding plate to protect fuel lines from entrapment by the transmission**

### Protection from Hard Points on Bullet Vehicle

It was found that the front hood of the bullet Caprice was peeled away in the side impact tests exposing many sharp edges. Figure 16 shows the protruding alternator and other sharp edges that scraped the bottom of the pickup tank in a crash test. These hard points may have contributed to the tear in the OEM tank shown in Figure 10. For the center-mounted tank, the hard points resulted in scrapping and minor gouging of the tanks. However, no leakage occurred from this source in any tests of the center-mounted tank.

**Figure 16. Caprice engine compartment after test showing hard points that contacted the fuel tank**

In one test of the center-mounted tank a plastic shield was installed so that it covered the bottom and sides of the tank. During the test, the shield remained securely in place and provided additional protection from hard points on the impacting vehicle. The thickness of the center-mounted tank proved to be adequate to resist the contacts with the hard points on the Chevrolet, so the shield was not tested further. Notwithstanding the benefits of the shield in a crash environment, the shield would also provide protection from wear and tear caused by typical road hazards (i.e. rocks and dirt).

**Filler Neck Check Valves**

On many of the tanks, a reverse flow check valve was installed. It consisted of a spring and ball arrangement that would prevent excessive fuel spillage in the event that the fuel filler tube was severed or torn from the tank and if a rollover occurred. The functionality of these valves was never required, as the filler tube remained intact and connected to the tank during all of the tests.

The diameter of the check valves used during testing was smaller than the diameter of the filler hose on GM trucks and consequently it introduced a flow restriction that increased the time needed to fill the tank. Therefore, from a practical perspective, the diameter of the check valve must be increased such that refueling is not impeded.

**Self-sealing Breakaway Connectors**

Self-sealing breakaway connectors were installed on the fuel delivery and returns lines on the racing fuel cell. In a Caprice test, the fuel lines connectors disengaged and no leakage occurred. The self-sealing breakaway connectors are shown in Figure 17 before and after the test.

a) 

b) 

**Figure 17. Self-sealing break-away couplings in fuel line before test (a) and after test (b)**

**Fire Panel**

An additional fire prevention countermeasure was tested concurrently with the second test with the automotive fuel cell. “Fire suppressant panels” were affixed to the sides and bottom of the fuel cell after it was installed in the vehicle. The panels were held in place with a double sided adhesive tape. If fractured, these panels emit a fire suppressant powder that forms a dust cloud that is supposed to extinguish a fire.

The fire suppressant panels that were affixed to the tank fractured during the test and a cloud of fire suppressant powder could be seen in the video engulfing the underside of the truck. The fire panels can be seen in Figure 18 before the initiation of impact and after the release of the fire suppressant has begun.

a)  b) 

**Figure 18. Fire panels installed on the fuel cell [see arrows in (a)] and the initiation of the cloud of fire suppressant during impact (b)**

The suppressant cloud remained for the duration of the impact event and was still present approximately 3 seconds after impact when the truck rolled over, at which time forward movement of the vehicles had ceased. The suppressant cloud, immediately after the truck rolled onto its side, is shown in Figure 19.

**Figure 19. Fire suppressant cloud immediately after the truck rollover**

## SUMMARY AND CONCLUSIONS

Eighteen full-scale tests were performed on six alternatives to the sidesaddle tanks on 1973 to 1987 GM C/K pickup trucks. The critical test configuration was an 80.0 km/h (50 mph) lateral impact from a Chevrolet Caprice. Two alternatives tank systems were selected for further test and evaluation. The evaluation included FMVSS 301 frontal, rear and lateral type tests conducted at higher severity than required by FMVSS 301.

Three tank systems were evaluated that maintained the tank in the sidesaddle location. These were: a tank protection system, an auto racing fuel cell and an after market plastic tank. None of these succeeded at preventing or maintaining fuel leakage within the prescribed acceptable limits when subjected to the 80 km/hr side impact by a Caprice. The fuel leakage limits were based on the FMWSS 301 performance requirements. The protective frame system that was intended to redirect impact loads around the tank to the vehicle frame was not capable of withstanding the downward moment imposed by the bumper of the impacting vehicle. The materials of the plastic tank and the fuel cell offered limited resistance to damage from slashing or puncture. Improvements to the design of these systems to withstand the side impact loading were considered possible but impractical due to the increase cost and complexity. Less costly alternatives were found, so enhancements to these designs were not pursued.

The rear mounted tank, although capable of successfully passing the side impact collision, was not considered a viable alternative due to cost and the potential for damage in a severe rear impact collision.

The remaining two alternatives, namely the center-mounted tank and the bed-mounted tank, improved crashworthiness through relocation of the tank. In the center-mounted location, the tank was removed from direct loading and additional protection was afforded by the vehicle's frame rail. Additional tank features, such as rounded and chamfered corners, were incorporate in the center tank design to enhance its resistance to damage. The bed-mounted tank system consisted primarily of standard OEM components relocated to the bed of the truck. Both systems performed exceptionally well under the severe crash conditions of the test program and underwent numerous additional evaluation tests.

Of all the systems tested, the bed-mounted system is the most crash resistant and easiest to implement. However, a practical limitation of the system is the reduction in cargo capacity associated with the placement of the tank in the bed of the truck.

In general, the most effective means of improving the tank's crashworthiness was by positioning it so that direct loading is minimized or avoided altogether. The same strategy was also be applied to the all other fuel system components, such as, fuel lines and tank selection valves for multi-tank systems. The shielding of the fuel lines provided a remedy for the fuel line crushing experienced during testing.

Technologies were tested that involved two types of check valves in the fuel filler pipe, abrasion shielding of the tank, self-sealing-break-away fuel line couplings, and fire suppressant panels. The ball check valves in the fuel filler tubes of the center-mounted tanks were not exercised during the tests because the filler tube always remained in tact. The abrasion shielding of the center-mounted tank performed satisfactorily, but was not required to prevent tank leakage in the tests. The self-sealing-break-away couplings prevented fuel line leakage when the bladder tank to which they were connected was dislocated from the vehicle. The flapper valve in the fuel filler pipe of the bladder tank also functioned as designed. The fire panels provided a cloud of fire suppressant during and after the crash, their efficacy in preventing a fire was not tested.

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All reports and videos of the tests referenced in this paper are available from the FHWA/NHTSA National Crash Analysis Center at The George Washington University.

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