A Center-Mounted Fuel Tank for GM C/K Pickup Trucks

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ABSTRACT

The sidesaddle fuel tank on 1973-1987 GM C/K pickup trucks has been the subject of extensive test and evaluation. Tests conducted by NHTSA led to the conclusion that the placement of the tank outside of the vehicle frame rail increases its susceptibility to damage and leakage during severe side impact collisions. Various alternative tank designs and placement strategies to mitigate tank leakage have been evaluated during a recently completed research program. One strategy, designated the center-mounted tank, relocated the tank inside the frame rails. Crash tests demonstrated that the center-mounted tank was able to withstand an 80 km/hr side impact test condition that caused excessive leakage in the sidesaddle tanks. Crash testing of 11 trucks showed that the center-mounted tank survived side, front and rear crash tests more stringent than required by the Federal Motor Vehicle Safety Standard for fuel integrity.

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 degree 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 (4000 lb) 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 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 rail.

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]. Although the sidesaddle design was largely discontinued in the 1988 and later models, it persisted on a few configurations until 1991. 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 impacts. The ODI's analysis of 1979-1993 real-world accident data indicated 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. 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. However, the ODI concluded that the severities of fatal side-impact crashes involving fire were generally more severe than those specified by the FMVSS 301 standard. Crash testing disclosed that the C/K pickup's fuel system exceeded the leakage requirements of the 301 standard when impacted in the side by a Chevrolet Caprice traveling at 80 kph (50 mph). Competitive pickup models were found to survive this test.

During the defects investigation, NHTSA conducted 25 or more crash tests of the 1986/1987 C/K, Ford F-150, and Dodge Ram 100 pickups. The C/K passed the FMVSS 301 standard for side impacts when tested at 32.0 km/h (20.0 mph). It also passed the 301 standard when the test speed was raised to 52.5 km/h (32.8 mph). NHTSA also conducted a series of tests that was more representative of crashes in which fires had occurred. The defining test condition was a side impact by a Chevrolet Caprice traveling at 80.0 km/h (50.0 mph) and oriented at 60° relative to the centerline of the truck. The C/K fuel systems leaked after being subjected to this test, while the F-150 did not. Test dummies in the crashed vehicles indicated that the 50 mph impact by a Caprice did not produce excessive injury measures.

On April 9, 1993, ODI recommended 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 existing tank designs and readily available technologies [Keown et al, 1999] identified six possibilities, which included:

1. Adding a protective frame around the existing sidesaddle tank.
2. Installing a custom fabricated tank inside of the vehicle's frame.
3. Replacing the sidesaddle tank with an auto racing fuel cell.
4. Replacing the sidesaddle tank with an after market fuel tank installed in the spare tire wheel well located underneath the bed of the pickup aft of the rear axle.
5. Replacing the existing sidesaddle steel tank with a plastic tank designed specifically for the C/K trucks.
6. Replacing the sidesaddle tank with a bed mounted tank system.

All six alternatives were installed in 1985 to 1987 C/K pickup trucks and subjected to full-scale tests at elevated impact speeds compared to FMVSS 301 requirements [Keown et al, 2000]. Based on the favorable results obtained, the center-mounted tank and the bed-mounted tank were selected for further development and testing. This paper presents the continued development of the center-mounted tank.

PICKUP TRUCK SELECTION

The C/K pickup trucks selected for modification and testing were chosen from the 1985 to 1987 model years. The principal reasons for this selection were that the earlier models were less plentiful, were more likely to be in poor shape mechanically and were more likely to have excessive corrosion of the frame. All the trucks were purchased in or around the city of Ottawa, Canada, where the use of road salt in the winter accelerates the corrosion of vehicles. A certain amount of corrosion was present on each truck in the test program. However, to reduce the variability in the testing, trucks with extreme frame corrosion were excluded.

The condition of similar trucks from regions with milder winters and where road salt is not used would no doubt have less corrosion. However, the trucks that were used were considered to represent a less than optimal vehicle condition that would typify corrosion levels more severe than most 1985 and later C/K trucks currently on the road. Hence any tank system that performed adequately on the tested trucks would likely perform equally well on a less corroded vehicle.

The 1973 to 1987 line of C/K trucks were available in two and four-wheel drive with a short or long bed and three maximum payload ratings that included ½ ton (1500 series), ¾ ton (2500 series) and 1 ton (3500 series). Ten of the eleven trucks purchased for the development of the center-mounted tank were the two-wheeled drive, 1500 series, long bed version and one was a four-wheeled drive version of the same truck.

POSITIONING OF THE CENTER MOUNTED TANK

An objective of any tank relocation strategy is to install the tank in a position that would be less susceptible to direct loading from an impacting vehicle. One of the best locations in the C/K pickup truck to accomplish this is in between the frame rail.

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 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 on the first truck the exhaust system was re-routed to the right side of the drive shaft. This was believed to introduce an unnecessary cost to the retrofit, therefore, for the remaining trucks the center tank was installed on the right side, necessitating a longer filler tube to be routed from the filler door located on the left side of the truck to the tank spout. A typical tank installation is shown in **Figure 1**.

Figure 1: Typical center-mounted tank installation.

TANK DESIGN

The suitability of existing fuel tanks from various manufactures was evaluated for compatibility with the space constraints of the selected new tank location inside of the right side frame rail. A Ford Ranger tank came closest to fitting, however its geometry did not optimize the available space nor did its mounting system lend itself to easy installation without modifications. Considering these limitations, effort was directed instead at developing a tank specifically for the desired location.

The design of the center mounted tank and its associated mounting brackets changed based on information gained during the test program. As testing progressed the center-mounted tank design evolved to incorporate features to improve its crashworthiness.

The first 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 is two fold: Firstly, the thicker steel simplified the manual welding process and secondly, and probably most importantly, it offered improved resistance to damage. The tank was held in place at three locations with the front of the tank supported by a cantilever support arm that fastened to a frame cross member. The middle of the tank was strapped down to a substantial "L" shaped bracket that bolted directly to a frame rail and supported the tank from underneath. A strap that attached to the frame rail and a cross member supported the rear of the tank.

The fluid volume of the first tank was 64.4 litres, 11.4 litres less than the OEM tank. 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. To increase volume, the tank was lengthened to the rear. The overall volume was increased to 71.9 litres for subsequent tanks.

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.

A four-wheel drive GM 1500 series pickup truck was tested in the eighth tests where differences in the frame and transmission necessitated modifications to the tank and mounting brackets that were previously used. The front end of the tank was shortened by 152.4 mm because of interference with the four-wheel drive transfer case. Additionally, a section of the right side of the tank was removed to allow clearance for a stiffening bracket that is added to the cross frame rail on the four-wheel drive truck. To regain some of the lost fuel volume, the tank was extended by 38.1 mm at the rear. However, as a result of all of these changes the volume of the tank decreased from 71.9 litres to 65.5 litres.

The presence of the four-wheel drive transfer case necessitated replacing the front cantilever support used in previous installations with a tubular steel "L" shaped bracket similar to the middle tank support bracket. Although the change to the tank mounting system was implemented to address the specific issues related to the four-wheel drive truck, it was considered more robust and was used in all subsequent tests.

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, filler tube check valve and an after market sending unit. In one test a plastic cover provided additional protection to the bottom and both sides of the tank. 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.

In all the tests, except for one, an OEM sending unit was installed on the center-mounted tanks. The depth of the center-mounted tank is shallower than the OEM tanks thus requiring the fuel pickup tube to be shortened. Since the sending units are normally secured to the OEM tanks via a lock ring arrangement, installation on the custom fabricated tanks was accomplished by cutting the receptacle for the sending unit from an OEM tank and welding it to the custom tanks. The same lock ring arrangement could therefore be used to install the sending unit to the tank. In one test, however, an after market sending unit was used and was bolted directly to the tank. This sending unit did not provide connections for the vent and return lines, which necessitated spouts for these lines to be welded directly to the tank. Instructions for the installation of the final revision of the center-mounted tank are recorded in the report "Installation of a Center-mounted Fuel Tank in the GM 1500 Series Pickup Truck" [Fournier et al, September 2001].

TEST CONFIGURATION

The crash worthiness of the custom fabricated center-mounted tank was evaluated under various full-scale crash configurations. A bullet vehicle comprised of either a Chevrolet Caprice or a FMVSS 301 moving barrier collided into the side of six GM 1500 series pickup trucks retrofitted with the center-mounted tank. The impact speed of the Caprice was nominally 80.0 km/h into a stationary pickup truck. The angle of impact was 60° from the front of the truck and inline with a point on the truck's centerline located between the cab and the truck bed. In one test the Caprice was replaced with a FMVSS 301 rigid moving barrier travelling at 64.2 km/h and oriented 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 2** and **Figure 3**.

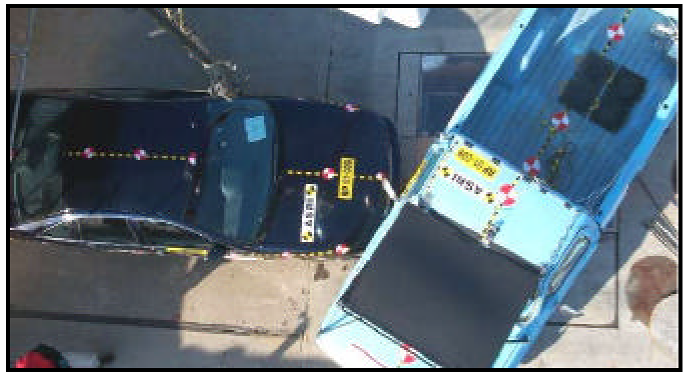

Figure 2: Typical vehicle alignment in side impact tests with a Caprice as the bullet vehicle.

Figure 3: 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.

Three 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 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. The second and third frontal tests were performed at an elevated nominal speed of 51.8 km/h. 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 and 56.2 km/h 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 center-mounted tank was further verified, as per the standard, by inverting the entire truck about the longitudinal axis in increments of 90°. The presence of leaks was again compared to the leakage limits specified in the FMVSS 301 rollover requirement.

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.

CINEMATOGRAPHY

Up to 8 high-speed film cameras were set-up to record the vehicle to truck impacts. This included two overhead shots, two underside shots from a pit, one left shot, one right shot and one onboard shot to record occupant movement. For some tests a second onboard high-speed camera was used. Furthermore an additional panning, real-time video camera was used to follow the bullet vehicle to impact. Each of the cameras recorded at 500 frames per second (fps) except for one pit camera that recorded at 1000 fps. The positioning of the cameras and the vehicle alignment are depicted in **Figure 4**.

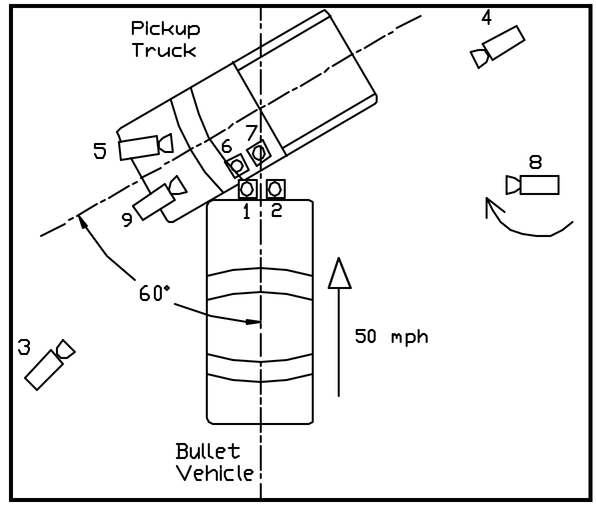

Figure 4: Test vehicle orientation and camera positions for RP 01-009 (other tests are the mirror of that shown).

Seven cameras were used for the FMVSS 301 style frontal and rear barrier testing. These included; two cameras on each side of the truck perpendicular to the line of travel, two cameras underneath the truck and one overhead. The camera framing rates were similar to those described above.

RESULTS

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 **Table 1** followed by a brief summary of each test [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.

Table 1: Summary of test configurations.

Test No.	Test Configuration	Impact Speed		Fuel Tank Leakage	Fuel Line Leakage
		(km/h)	(mph)		
RP 01-009	60° side impact by a Caprice	81.6	51.0	Pass	Pass
RP 01-036	60° side impact by a Caprice	81.4	50.9	Pass	Fail (1)
RP 01-037	90° side impact by a rigid barrier	64.2	40.1	Pass	Pass
RP 01-038	60° side impact by a Caprice	81.4	50.9	Fail (2)	Fail (2)
RP 01-039	60° side impact by a Caprice	81.4	50.9	Pass	Pass
RP 02-028	Frontal into rigid barrier	49.0	30.6	Pass	Pass
RP 02-029	Rear impact from a rigid barrier	49.0	30.6	Pass	Pass
RP 02-030	60° side impact by a Caprice to a 4x4 truck	80.0	50.0	Pass	Pass
RP 02-031	Rear impact from a rigid barrier	56.2	35.1	Pass	Pass
RP 02-032	Frontal into rigid barrier	51.8	32.4	Fail (3)	Fail (3)
RP 02-096	Frontal into rigid barrier	51.8	32.4	Pass	Pass

(1) The tank was not damaged. The leak stemmed from a crushed fuel tank switching valve, not required for the center-mounted tank.
(2) The fuel line leading to the engine was severed and a small hole in the tank was discovered. The exhaust manifold was removed from truck prior to test resulting in unrepresentative load paths during side impact.
(3) The web on THM 400 transmission caused load concentration during rearward movement of the engine/transmission.

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.

TEST RP 01-009

The bullet vehicle for this test was a Chevrolet Caprice. The anti-rollover outrigger affixed to the truck on the opposite side of the impact failed and the truck rolled onto its side. An imperfect seal between the OEM sending unit and the OEM sending unit receptacle resulted in minimal leakage, that was well within the allowable limits. The test results provided encouragement of the viability of this alternative to withstand not only severe side impact, but also rollover.

TEST RP 01-036

This test was an impact with a Chevrolet Caprice. Although the tank survived the collision all of the contents of the tank were completely expelled. A second tank was installed in the bed of this truck requiring a fuel line switching valve so that the motor could draw fuel from either of the two tank systems. This valve was crushed between the frame rail and the transmission housing during the test, severing the fuel lines from both tanks leading to the engine. All of the fluids from both tanks were siphoned under the influence of gravity.

It is worthy to note that had only the center tank been installed a switching valve would not have been required and the tank would have passed the test. With this in mind the fuel lines were plugged and the tank refilled such that a rollover test could be performed. There was no leaking observed during the rollover test.

TEST RP01-037

This was a FMVSS 301 side impact barrier test with an elevated impact speed of 64.0 km/h instead of 32.0 km/h as specified by the standard. Passing at such an elevated impact speed would suggest compliance at the appropriate lower standard test speed. Maximum loading of the tank systems was achieved by aligning the barrier such that the crush zone on the truck was aft of the A-pillar and forward of the rear axle. There was no fuel spillage from the center-mounted tank following the collision.

TEST RP 01-038

The bullet vehicle in this test was a Chevrolet Caprice. The fuel line leading to the engine was crushed and severed between the right side frame rail and the transmission housing resulting in a substantial gravity induced leak. The manifold pipe that was normally routed between the frame rail and the transmission may have prevented the damage to the fuel line by acting as a rigid spacer and providing clearance for the fuel line. However, it was remove to help achieve the vehicle target weight.

The center tank sustained substantial denting from various sources including the drive shaft, the threaded end of a bracket strap and the impinging vehicle. Regardless of the severed fuel line the integrity of the tank itself was to be verified by refilling it and subjecting the truck to a rollover test. However, during the refilling a leak exceeding the allowable limit was discovered in the side of the tank. The hole was located along the lower edge of the tank in a crease created by the tank bracket. The inversion of the right angle edge of the tank resulted in high tearing stress and consequently the hole. For subsequent tests the tank and brackets were modified to minimize concentrated tearing stresses by incorporating tubular steel for the tank mounting bracket and by adding a radius to the bottom edges of the tank.

TEST RP 01-039

This was another test with a Chevrolet Caprice as bullet vehicle. There was an initial spray of fluid during the collision that was barely visible in the real time video that lasted for approximately 2 frames. The quantity of fluid that leaked could not be measured but was estimated to be less than 30 ml (1 oz). It is believed that the fluid was forced out from the connection between the filler vent line and the filler cap assembly due to the overpressure in the fuel tank. Within the first five minutes after impact an additional 9 ml (0.3 oz) leaked from the vehicle after which no further leakage was observed.

A shield placed over the fuel lines, which ran along the inside of the frame rail, to prevent damage from the transmission housing, was deformed from contact with the transmission. Additionally, the exhaust manifold, which was not removed from the truck as it was in the previous test, impeded relative translation of the frame rail towards the transmission. The lower flange of the frame rail imprinted itself in the right manifold pipe indicating substantial loading of that component.

TEST RP 02-028

This test was performed exactly according to the frontal procedures of FMVSS 301 including the installation of ballast in the truck bed. Following the test, the tank was found to be leaking, within the allowable limit, from a pinhole in a welded corner of the tank. The high-speed video from under the truck revealed that the center tank slid forward through the middle and rear straps and contacted the transmission housing and/or a frame cross member. The front strap securely held the tank, however, the cantilever bracket to which it attached buckled. Loading to the front end of the tank cause the tank to bulge, resulting in the pinhole.

To prevent failure of the front tank bracket in subsequent tests the cantilever bracket was replaced with a bracket similar to the existing middle bracket.

TEST RP 02-029

This test was performed according to the rear impact barrier requirement of the FMVSS 301 standard, including the installation of ballast in the truck bed, and it passed without any fuel leakage. Post crash observations revealed that the center-mounted tank had displaced toward the front. However, a review of the high-speed film from beneath the vehicle indicated that the tank initially moved towards the rear of the truck and was arrested by the rear frame cross rail. The forward movement of the tank likely resulted from a secondary impact of the truck with hay bails placed at the end of the impact tarmac. A tank catch plate was added for subsequent testing to minimize the forward tank displacement.

TEST RP 02-030

A Chevrolet Caprice was the bullet vehicle in this test. This was the only test of a four wheel drive 1500 series pickup truck, and as such the vehicle set-up specifications reported in TRC's report 930324 were not applicable.

The center tank experienced little to no damage to the under side of the tank but the four wheel drive transfer case contacted the front end of the tank along its inside vertical edge causing minor damage. The integrity of the fuel tank remained intact and was confirmed by an inversion test.

TEST RP 02-031

This rear impact test was performed similarly to test RP 02-029 with three exceptions. Firstly, a spare tire was installed in the correct location underneath the truck aft of the rear axle. Secondly, there was no ballast weight attached to the bed of the truck as per the requirements of FMVSS 301. Thirdly, an elevated impact speed of 56.0 km/h was targeted instead of the previous 48.0 km/h. In lieu of the ballast weight, a second fuel tank containing 72 litres of solvent was installed in the truck bed. The approximate weight of this system, including the solvent, was a 91 kg.

The center-mounted fuel tank moved rearward approximately 12.7 mm to 25.4 mm during the initial impact from the barrier. However, the modified mounting brackets and straps installed for this test prevented further forward movement of the tank during a secondary frontal impact with hay bails. The tank itself was not damaged during the test and no fuel leakage was observed.

TEST RP 02-032

This frontal barrier test was performed similarly to test RP 02-028 with two exceptions. First, the test speed was increased to 51.2 km/h from 48.0 km/h and secondly, the ballast weight that was bolted to the floor of the box in the previous frontal test as per the requirements of FMVSS 301 was replaced with unrestrained plywood. This type of loose payload was considered to be more representative in simulating loading to a secondary tank system mounted in the bed.

It is estimated that at the elevated impact speed of 51.2 km/h the tank underwent approximately 25.4 mm of forward displacement indicating the effectiveness of the changes in the mounting brackets. Although movement of the tank was minimal, crushing of the front end of the truck pushed the transmission rearward, contacting the front inside edge of the center tank. The damage was sufficient to compromise the integrity of the tank and a fluid leak, exceeding the specified flow rates, ensued.

An upgraded THM 400 3 speed transmission was installed in this truck instead of the usual THM 350 3 speed transmission. The THM 400 transmission is larger with potentially more aggressive stiffening gussets, therefore, it is possible that the integrity of the tank may have remained intact had this test been run on a truck with a smaller transmission.

To improve on the center tank's performance in a truck with a similar transmission the tank was shortened in the front and lengthened at the rear to regain the lost volume. Additionally, the front corner was chamfered to minimize contact between a 90° corner on the tank and an aggressive edge on the transmission.

TEST RP 02-096

This frontal barrier test was performed similarly to test RP 02-032 except that no payload was placed in the bed of the truck. The tested truck was also equipped with the THM 400 3 speed transmission.

Similarly to test RP 02-032, the center tank did not move relative to the frame rails, however, the front-end crush pushed the transmission rearward, contacting the left side of the center tank. The damage was limited to denting without compromising fuel containment.

The chamfered inside front corner of the tank received what appears to be only a minor glancing blow from the transmission indicating the effectiveness of the tank modification.

There was no leakage following the test.

DISCUSSION

GENERAL TEST REPRODUCIBILITY

The input parameters for the four side impact tests with the Chevrolet Caprices were similar. The vehicle alignment at impact was within 45.7mm of the static pre-crash alignment and in fact it was within 25.4 mm for three of the tests. The impact speeds ranged from 81.4 km/h to 81.6 km/h and the tested mass of the of the vehicles ranged from 1,995 kg to 2,004 kg for the trucks and between 1,812kg and 1,815 kg for the bullet vehicles. Additionally, the ride height of the trucks, with the exception of the four wheel drive truck, was within 12.7 mm of each other; the same is true for the bullet vehicles.

The similarity in the test set-up and input conditions resulted in similar vehicle kinematics. Following contact with the truck, the front end of the bullet vehicle was pushed downwards under the truck, lifting the truck up and carrying it in the direction of impact. The resulting damage to the vehicles, from test to test, was also similar (see **Figure 5**).

Figure 5: Typical pickup truck damage following a collision from a Caprice.

ANTI-ROLLOVER BAR

To protect the film equipment mounted on the hood of the pickup truck, an anti-rollover bar was installed on the truck opposite the struck side of the vehicle. In test RP 01-009 the rollover bar failed and the truck rolled onto its side. This raises an issue as to whether or not the anti-rollover bar can affect the severity and outcome of the impact and subsequently, the damage to the tank.

In each of the center-mounted fuel tank tests the bullet vehicle tended to submarine under the trucks. In so doing it created an upward force on the underside of the truck, which was, applied closer to the struck side of the vehicle. The application of this force promoted rotation of the truck about its longitudinal axis (ie. rollover). If the truck rolled sufficiently, the anti-rollover bar would contact the ground creating a restoring moment to the truck thus increasing the loading to the tank, as compared to a truck that was free to rollover. In effect, testing with the anti-rollover bar in place results in a worst case scenario.

HAZARDS FROM STRIKING VEHICLE

It was found that the front hood of the bullet vehicle is peeled away in the side impact tests exposing many sharp edges. These hard points have resulted in scrapping and minor gouging to the tanks. However, no leakage occurred from this source in any tests. If required, protection from this kind of damage may be achieved by placing a shield over the steel center tank similar to the plastic shield used in test RP 01-036 or similar to the plastic shields installed on many current model vehicles.

CORROSION

To varying extents corrosion was present on all the pickup trucks tested. Although trucks with excessive corrosion were not selected for the testing, clearly any amount of corrosion will decrease the integrity of the trucks' frames compared to that of a "new" vehicle. This in turn would influence the trucks' resistance to impact and consequently the amount of protection afforded to a center-mounted tank. The two trucks with center mounted tanks that were crashed into a barrier at 32 mph had more structural deformation than the new truck crashed at 35 mph in NHTSA's 1987 NCAP tests. In effect, the center-mounted tanks of this test program were subjected to loading conditions that were more severe then the original design conditions and in trucks that were less structurally sound.

CONSIDERATION FOR CENTER MOUNTED TANK INSTALLATION

The center mounted tank has been developed primarily around the General Motors two wheel drive, 1500 series pickup truck (model years 1985 to 1987) with additional installations in a four wheel drive version of the truck. These configurations represent a major portion of possible variations, but there are many other configurations. A review of various models was conducted to ascertain if the center tank may be installed in other versions of the truck. This is summarized in **Table 2**.

A parallel research project conducted testing of a bed-mounted tank that would be suitable for short bed pickups [Fournier, 2002].

Table 2: Feasibility of installing the center-mounted tank in various models of the GM pickup truck.

<table>
<tr><th>No</th><th>Truck Description</th><th>Notes</th></tr>
<tr><td>1</td><td>Standard box, 2x2, 1500</td><td><u>Standard tank [A].</u> The center tank was designed around this model of pickup. All the systems components can be installed without modification.</td></tr>
<tr><td>2</td><td>Standard box, 4x4, 1500</td><td>The standard tank must be shortened at the front by 6 inches and increased in the rear by 1.5 inches. Additionally, a cut-out must be provided to clear a stiffening gusset on the cab mount cross member.</td></tr>
<tr><td>3</td><td>Standard box, 2x2, 2500</td><td rowspan="2">The standard tank should fit.</td></tr>
<tr><td>4</td><td>Crew cab, 2x2, 2500</td></tr>
<tr><td>5</td><td>Short box, 2x2, 1500</td><td rowspan="5">Neither the standard tank nor the modified tank of truck type 2 would fit in these shortened box pickup trucks. They are to long.</td></tr>
<tr><td>6</td><td>Short box, 4x4, 1500</td></tr>
<tr><td>7</td><td>Short box, 2x2, 2500</td></tr>
<tr><td>8</td><td>Short box, 4x4, 2500</td></tr>
<tr><td>9</td><td>Step side short, 1500</td></tr>
<tr><td>10</td><td>Dually, 2 door</td><td>The standard tank will fit if only one tank was originally installed. For dual tank trucks the modified tank of truck type 2 is required.</td></tr>
<tr><td>11</td><td>Standard box, 4x4, 2500</td><td rowspan="3">The modified tank of truck type 2 is required.</td></tr>
<tr><td>12</td><td>Crew cab, 4x4, 2500</td></tr>
<tr><td>13</td><td>Dually, 4 door, 4x4</td></tr>
<tr><td colspan="3">Note: A- The tank installed in this truck is considered the "standard" center tank. Any alterations to the standard are noted in this table.</td></tr>
</table>

CHECK VALVES AND TANK FILL TIMES

The fuel filler hose is quite large in diameter and, if severed, could leak significant amounts of fuel. To prevent this from occurring, a check valve was added to the trucks' fuel tanks in test RP 01-036 to test RP 01-039. Following each of the tests the check valve remained intact and functional.

Readily available, off the shelf check valves were purchased from G.T. Products at a cost of approximately $26.00 US and were adapted to the center-mounted tanks. The valve was designed for a 25.4 mm diameter filler hose and not the 47.6 mm diameter hose of the GM pickup trucks. Consequently, the flow restriction created by these valves resulted in longer tank filling times.

SUMMARY

Figure 6: Center mounted tank and components

The components of the center mounted tank system that evolved from the development program is shown in Figure 7.

Center-mounted fuel tank systems were installed on eleven GM 1500 series pickup trucks, one of which was a four-wheel drive model. Five of the trucks, including the four wheel drive truck, were impacted on the side by a Chevrolet Caprice angled at 60° from the front of the truck and travelling at a nominal speed of 80.0 km/h. An additional truck was impacted by a FMVSS 301 rigid moving barrier travelling at 64.0 km/h perpendicular to the longitudinal axis of the truck. Three frontal and two rear impact tests were performed on the remaining five trucks. The frontal tests were performed at 48.0 km/h to 52.0km/h, whereas the rear impacts were performed at 49.0 km/h and 56.2 km/h.

It was found that the right-angled edges on the center-mounted tank could invert from a concentrated load resulting in tearing of the tank. To distribute loading associated with such an occurrence, a radius was incorporated in the tank's lower edge and the center mounting bracket was changed to include a radius along the edges contacting the tank.

Excessive fore-aft movement of the center-mounted tank was identified during the first of the frontal and rear impact tests. This movement was prevented during subsequent testing by incorporating a tank catch plate with the front mounting bracket.

Various transmissions were available on the GM 1500 series pickup trucks, the largest of which posed an increased hazard to the front of the tank in a frontal collision. Shortening the tank to provide additional clearance and chamfering the inside front vertical edge of the tank to minimize concentrated tank loading reduced the potential of damage from the transmission's tailstock.

The resulting vehicle damage during the four tests involving the two-wheel drive trucks and the Caprice was very similar under similar test conditions and vehicle preparation methods, indicating good test reproducibility.

The anti-roll bar that was installed on each of the trucks was shown to influence the kinematics of the truck, possibly resulting in greater loading to the center-mounted tank.

In one test the protection of the fuel lines running from the engine to the tank was inadvertently diminished when the exhaust manifold was removed in order to achieve a desired test weight for the truck. In later tests the manifold was left in place and an additional protective cover was placed over the fuel lines that were routed on the inside of the truck's frame rail.

The front of the bullet vehicles had many sharp edges, particularly underneath the hood, which gets peeled away during a test. These hard points resulted in scrapping and gouging of the tanks, but in no case caused leakage. Additional, protection from this kind of damage can be achieved by placing a shield over the center tank.

The check valve that was installed on four of the center-mounted tanks could create a flow restriction resulting in longer tank filling times. None of the tests resulted in fuel spillage from the filler line. However, a check valve may offer added safety. If a check valve is to be incorporated into the fuel tank system it must have a large enough diameter so as not to impede filling.

Despite best effort to obtain trucks with as little corrosion as possible, varying degrees of corrosion was nevertheless present on all the pickup trucks tested which, undoubtedly, had an effect on the trucks' resistance to impact and consequently the amount of protection afforded to a center-mounted tank. The tanks were therefore subjected to loading conditions that are more severe than the original design conditions.

The test reports and test videos of each individual crash test were documented on a CD (Biokinetics, March 2002) that is available from the Automotive Safety Research Institute.

The results of full scale testing of the center-mounted fuel tank was successful in that, of the eleven test performed, damage to the tank itself resulting in excessive fluid loss occurred in only two instances. However, in both instances the tank design was improved and in subsequent tests the tank produced favorable results. The center-mounted tank has been shown to be well protected in a variety of crash configurations that include frontal, rear and lateral impacts.

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