

# Heavy Truck Rollover Crashworthiness Utilizing Sled Impact Testing

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**Abstract** - Rollovers continue to be a major source of heavy truck fatalities when compared to other accident modes. Real world rollover accidents are analyzed and two distinct damage patterns are identified. Damage to heavy truck roofs can occur from lateral loading that transitions to vertical roof loading as the vehicle rolls onto its side and then over onto its roof. A second load path can occur when the vehicle has rolled onto its side and furrows into the ground generating large longitudinal friction forces between the roof and ground. A review of the previous literature and various test methodologies are presented. A sled impact test methodology is presented which allows for structural assessment of a heavy truck cab's crashworthiness in both of these loading environments. Two test series are presented using the sled impact test methodology in order to analyze real world truck rollovers using varying impact platen and contact angles. The structural deformation and failure patterns were found to be consistent with damage seen in real world accident vehicles. In each case, a second equivalent truck cab was then reinforced and tested under similar conditions to evaluate the energy management and crush resistance of a stronger cab structure. These structural reinforcements demonstrated a substantial reduction in roof crush and protected the survival space of the occupant compartment. The sled impact test procedure is an effective method for testing the structural performance of a heavy truck cab in a variety of loading scenarios comparable to real world accidents and ascertaining the load and energy load levels in these accident modes.

## INTRODUCTION

Accident statistics have long shown that heavy truck rollovers are an extremely dangerous accident mode for truck drivers and their passengers. In 1986, the National Highway Traffic Safety Administration (NHTSA) produced a study indicating that approximately 1,000 heavy truck occupants are killed in crashes every year [1]. They identified rollovers as one of the key factors that play a contributing role in causing those fatalities. The study also recognized the need to improve truck cab structures to "control and minimize the extent of cab intrusion so that ... the occupant survival space is maintained." Researchers from the University of Michigan Transportation Research Institute (UMTRI), reported in 1991 that approximately 60% of all heavy truck driver fatalities were associated with rollover accidents [2]. They further concluded that the existing cab structures were not strong enough to resist the forces produced during rollovers and that truck drivers had a 50% chance of being injured in a rollover even if they were restrained. If the truck did not rollover, the risk of injury drops by a factor of 10. The National Transportation Safety Board (NTSB) presented analysis on 189 heavy truck tow-away accidents in 1988 and noted that in many of the accidents, the structural design of the cab did not provide adequate protection for the driver [3]. "Many of those accidents involved an overturn at legal highway speed in which the top of the tractor cab was crushed to the level of the instrument panel, resulting in little or no survival space for the driver". In 1991 Campbell reviewed these NTSB accident files and determined that there was not sufficient survival space in 65% of those accidents [4]. In 2001, the National Institute for Occupational Safety and Health (NIOSH) investigated firefighter deaths from water tank truck rollovers and found that 20% of United States firefighter deaths each year are from motor vehicle accidents and that cases involving water tankers are the most prevalent of these motor vehicle incidents [5]. In its 2007 Factbook, UMTRI reports that a total of 796 truck drivers were fatally injured 53% of these fatalities were involved with rollovers, see Table 1 [6]. The percentage of rollover involved fatalities has not change appreciably in the last two decades.

Table 1: Excerpt of Table 4-7 from Reference [6]

| Accident Type               | Fatal Injuries | Incapacitating Injuries |
|-----------------------------|----------------|-------------------------|
| Rollover only               | 199            | 42                      |
| Rollover and fire           | 53             | 4                       |
| Rollover and ejection       | 157            | 2                       |
| Rollover, fire and ejection | 9              | 0                       |
| Rollover Total              | 418            | 48                      |
| <b>Annual Total</b>         | <b>796</b>     | <b>208</b>              |

These statistics make clear that heavy trucks have high propensity for occupant injury in rollover and that additional design considerations need to be made for heavy trucks in the rollover accident mode.

**PREVIOUS RESEARCH AND TEST METHODS**

The Swedish Impact Test is a heavy truck test method that has been used by Volvo since 1959 to test their heavy truck cabs ability to withstand rollovers [7]. This methodology is comprised of three tests. The first test subjects the truck cab roof to a distributed, static vertical load of up to 33,075 lb (15,000 kg). After this, a cylindrical pendulum weighing more than one ton is swung into one of the cab’s front A-pillars from a height of up to 10 feet (3.0 m). Finally, in the third test, another square pendulum weighing approximately a ton strikes the rear wall of the cab with the same amount of energy. In order to pass the Swedish impact tests, the same truck cab, having been subjected to all three tests, must maintain the occupant survival space, see Figure 1.

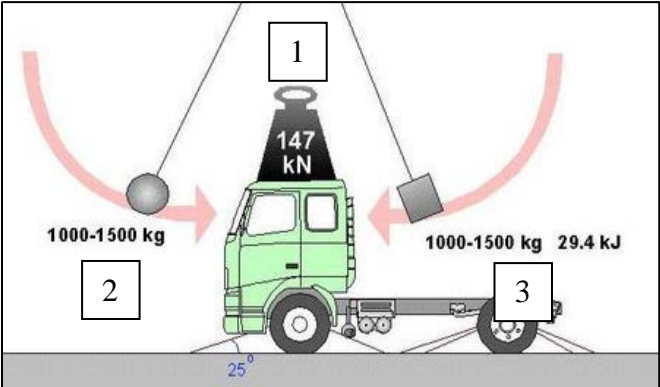


Figure 1: Swedish Impact Test Configuration

The survival space concept has been well understood since the 1950s, when DeHaven presented packaging engineering principles for the increased protection and safety of valuable goods in transit [8]. Beginning in the late 1960s most auto manufacturers incorporated the concept of “survival space” or “non-encroachment zone” within the occupant compartment, which is not to be intruded upon in a rollover. In 1969, Franchini published “The Crash Survival Space”, in which he discussed the importance of maintaining a post-crash survival space of 29.5 inches (74.9 cm) above the occupant’s H-point in all crash modes, including rollovers of cars and trucks [9], see Figure 2.

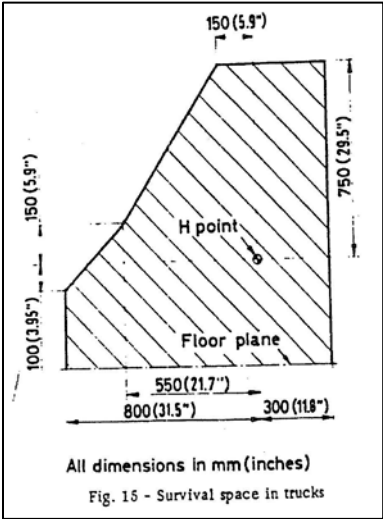


Figure 2: Figure 15 from Reference [9] on Survival Space in 1969

The need to provide rollover protection in construction equipment was recognized by Society of Automotive Engineers (SAE) as early as 1967 when it published its SAE J320 recommended practice [10]. This Recommended Practice J320 establishes the minimum performance criteria for roll-over protective systems (ROPS) for rubber tire self-propelled scrapers. The ROPS has to be able to absorb energy based on the weight of the vehicle in its lateral, or side, direction and subsequently withstand the full weight of the vehicle vertically, from above, without intruding in a “critical zone” around the driver which extends up 42 inches (107 cm) off the seat. For this recommended practice, an applicable vehicle weighing 22,046 lbs (10,000 kg) would need to absorb 28,050 ft-lb (38,031 J) prior to the vertical roof loading test.

The United States Army Corps of Engineers recognized construction machine rollover issues as well in 1967 in their safety and health requirements Manual EM 385-1-1 [11]. In this manual, section 18.B.13, rollover protective structures are required to be installed on water tank trucks having a tank height less than the cab. These ROPS systems must comply with the applicable SAE standard (such as SAE J320). As early as 1969, several states, such as Oregon and Washington, enacted rules requiring ROPS on commercial, industrial and material handling equipment [12, 13]. In 1972, the US Department of Labor’s Occupational Safety and Health Administration (OSHA) standard 1926.1000 established the need for ROPS on material handling equipment that is used in construction [14].

United Nations Economic Commission for Europe (ECE) Regulation 29, implemented in 1974, lays out uniform provisions for commercial vehicles, including heavy trucks [15]. Included in those provisions is a frontal impact test, roof strength test and rear-wall strength test. The roof strength test requires the roof to withstand the static, distributed weight of the maximum allowable front axle load up to 22,046 lb (10,000 kg). After the test is performed the cab must maintain a survival space allowing accommodation of a seated manikin representing a 50th percentile male occupant.

SAE J320 eventually evolved into “SAE J1040 (1988) - Minimum Performance Criteria for Rollover Protective Structures for Construction, Earthmoving, Forestry and Mining Machines” [16]. Recommended Practice J1040 specifically calls out the tractor portion of water wagons under the scope of the standard. An example of the loading required by SAE J1040, a 22,046 lb (10,000 kg) prime mover must withstand a side load of 21,372 lb (9,694 kg), absorbing 14,751 ft-lb (20,000 J) and then subsequently withstand 44,114 lb (20,010 kg) vertically and 17,097 lb (7,755 kg) longitudinally without intruding into the survival space defined in SAE J397b (1988) [17]. Today, this standard exists as the international ISO 3471 standard which notes that it exists to provide guidance to manufacturers of ROPS structures for the vehicles specifically listed as well as other machines [18].

In 1997, Australia implemented standard AS2294 for Earth-Moving Machinery- Protective Structures [19]. While very similar to SAE J1040, AS 2294 differs in that it specifically requires that any rigid frame service vehicle (e.g. heavy truck), comply with its rigid frame dumper ROPS-only requirements without intruding into the survival space defined by ISO 3164 (technically similar to SAE J397).

In 1998, SAE developed a recommended practice, SAE J2422, to evaluate heavy truck cab roof strength resistance in a 180-degree rollover [20]. This procedure, revised in 2003, has two phases for loading the roof, “a dynamic pre-load that simulates the side loading of the upper cab as the vehicle rolls past 90 degrees and a quasi-static roof loading that simulates the loading of the cab when the vehicle is inverted.” For the first phase, the truck cab is affixed to the ground at a roll angle of 20 degrees and the pre-load is applied by the vertical-faced of an impact sled to the truck cab’s roof, see Figure 3. The sled should weigh 5,000 to 15,000 lb (2,268 – 6,804 kg) and should impact the cab with a kinetic energy of up to 13,000 ft-lb (17,626 J). The second phase involves static loading the roof through its vertical axis until it reaches a load equal to the maximum capacity of the front axle up to 22,046 lb (10,000 kg) with no energy requirement. After both tests, the vehicle must exhibit survival space allowing for accommodation of the ECE Regulation 29 seated manikin.

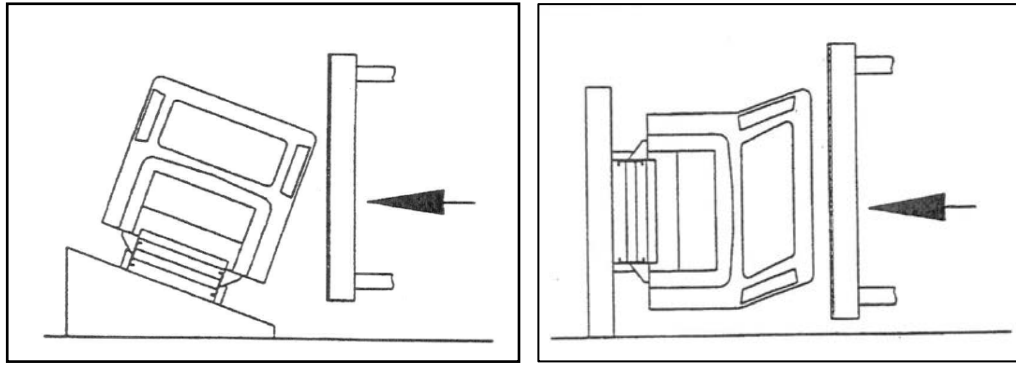


Figure 3: SAE J2422 Dynamic Pre-Load and Quasi-Static Roof Load Configurations

In 2005, Evans [21] reported on heavy truck FARS data and utilized the inverted drop test methodology to assess heavy truck cab performance. The case study presented involved a roll-cage reinforced cab dropped from 12 inches (30.5 cm) with a roll angle of 25 degrees and a pitch angle of 5 degrees. Evans also suggested other roof strength increasing methodologies that could provide improvements similar to that of including a rollcage. Batzer et. al. built on this work in 2009 [22] by testing a similar heavy truck rollcage in a FMVSS 216 static crush test and rolling a rollcaged heavy truck down a sandy hillside. The rollcage structure was placed on the inside of the cab adjacent to the existing structure. The rollcage weighed approximately 195 lb (88.6 kg) and demonstrated a crush resistance of 50,500 lb (224.6 kN) in a FMVSS 216 type test.

### **SLED IMPACT TEST SETUP**

Sled impact tests are a well understood approach to investigating vehicle response to dynamic loads, whether in the modelling of real world accidents or determining the performance of a vehicle's structure or safety system. These tests are routinely used in vehicle development and have several distinct advantages for structural testing. The loading is dynamic and will examine the actual response to the system in environments similar to real world accidents. These tests can be conducted at speeds, energy levels and orientations seen in these accidents. Energy requirements can be directly determined and examined by altering test parameters and comparing high speed test video with instrumentation. SAE J2422 utilizes a sled impact test for the dynamic preloading of the structure.

Two series of sled tests were conducted on heavy truck cabs in order to evaluate their roof structure performance under rollover loading conditions. Both test series were conducted in an effort to generate damage consistent with real world accidents. The sled impact tests were conducted consistent with the sled impact methodology outlined in the SAE J2422 but utilizing different input energies and impact orientations.

Each cab structure was inspected for defects prior to being tested. Various portions of the interior compartment trim were removed to reveal the cab's underlying structure and allow for analysis of its structural performance during testing. The cabs were then rigidly mounted to the test fixture at the desired orientations.

During testing, a sled fixture was accelerated toward the stationary cab by a falling mass suspended by a block and tackle arrangement. The sled was accelerated until just a few feet prior to the point of impact, at which point the sled coasted freely to impact. In each case, the sled was instrumented with accelerometers and the exterior of the occupant compartment roof structure was documented via 3-dimensional survey equipment before and after testing.

In each test series, the original equipment manufacturer (OEM) cab structure was tested, followed by a similar test conducted on an equivalent cab that had been structurally reinforced. In the first test series, the roof structure was integrally reinforced, either inside the existing structural section voids

and/or by adding additional sheet metal layers. In the second series, an external ROPS was fabricated to be mounted to the truck frame and extend above and around the exterior of the existing cab structure. The reinforced cabs were then subjected to similar test conditions as the OEM cabs.

### Test Series 1

A real world accident involving a Sterling A9500 series heavy truck was analyzed. In this accident, the heavy truck was involved in an on-road impact with a passenger car and subsequently exited the roadway before overturning onto its driver's side. The vehicle continued to slide on its driver's side, generating large frictional loads, before interacting with the sloped shoulder embankment adjacent to the roadway. The accident vehicle is shown in Figure 4.



Figure 4: Series 1 Accident Vehicle

In order to evaluate the roof loading and occupant compartment roof deformation from this accident, with a large frictional component, the following sled test set-up was utilized. Using the OEM cab frame mounts, the occupant compartment was rigidly mounted at a 90 degree driver's side leading roll angle with 35 degrees of pitch such that the sled striking platen would make initial contact with the driver's side A-pillar-header junction. The platen attached to the front of the sled was oriented at 20 degrees from vertical, see Figure 5.



Front View of Cab



Rear View of Cab

Figure 5: Series 1 Test Set-Up

As there was no publicly available roof strength data for this cab structure with the amount of crush resulting from this accident, a roof strength approximation was made and the test conditions were selected in order to achieve, or overshoot, the deformation level observed in the subject accident truck cab. The initial impact speed was targeted at 19 mph (30.6 kph) for an approximate energy of 60,000 ft-lb (81,349 J).

The deformation patterns from Test A and the accident vehicle were utilized to determine the location and the extent of reinforcement necessary to protect an occupant in this or other rollover impacts. A



second Sterling A9500 series heavy truck occupant compartment and driver's door were structurally reinforced based on this structural assessment. Due to the large door opening, it was determined that the door need to be reinforced to act both as a load path and to insure the door would remain closed and intact in the collision. The structural reinforcements included the addition of integral 4130 steel tubing and rigid polyurethane foam to the cab's structure. The total weight of the reinforcements was 220.3 lb (99.9 kg). These in-house retrofit reinforcements would weigh significantly less if implement in the production design process. With the implemented steel reinforcements welded in place, rigid polyurethane foam was then added to fill voids in the structure, such as the front header, side headers, rear header, A-pillars, B-pillars, and rocker rails, see Figure 6. The impact configuration for Test B was to be determined from the results of Test A compared to the accident vehicle.

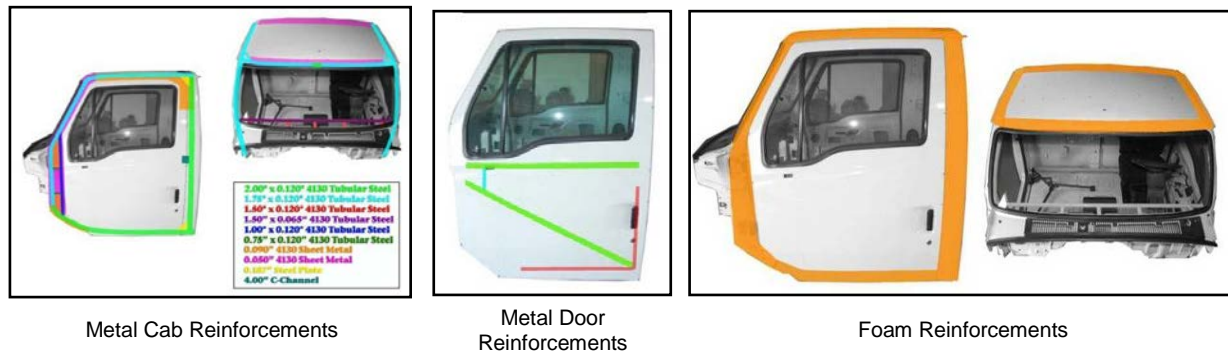


Figure 6: Cab Reinforcement Schematics

## Test Series 2

A real world accident involving a 1991 Ford L series heavy truck was analyzed. In this accident, the heavy truck equipped with a water tank was traveling at highway speeds when a tire failed causing the vehicle to leave the roadway before rolling passenger side leading and coming to rest on its roof. The accident vehicle is shown in Figure 7.



Figure 7: Series 2 Accident Vehicle

In order to evaluate the roof loading and occupant compartment roof deformation from this accident, the following test set-up was utilized. A production vehicle was to be subjected to a set of three sled impact tests. The energy input for Test I was chosen as the maximum recommended in SAE J2422 in order to establish the roof stiffness characteristics and energy absorption characteristics. The results of this test were used to determine the test configurations and energy input for Test II and III in order to produce the deformation seen in the accident vehicle.

The cab was mounted to a rigid barrier face at the angles specified below for each test, see Table 2. The impact sled, weighing 7,275 lb (3,300 kg) was accelerated to the target speed for each test and impacted the cab. The sled impact face was approximately a 5 foot (1.52 m) square flat surface and instrumented with 4 load cells, see Figure 8.

Table 2: Series 2 Test Setup

| Test Parameter  | Test I                     | Test II                    | Test III                 |
|-----------------|----------------------------|----------------------------|--------------------------|
| Target Velocity | 7.3 mph<br>(11.7 kph)      | 11.4 mph<br>(18.3 kph)     | 5.4 mph<br>(8.7 kph)     |
| Target Energy   | 13,000 ft-lb<br>(17,626 J) | 31,500 ft-lb<br>(42,708 J) | 7,000 ft-lb<br>(9,491 J) |
| Cab Roll Angle  | 55 Degrees                 | 70 Degrees                 | 90 Degrees               |
| Cab Pitch Angle | 0 Degrees                  | 15 Degrees                 | 0 Degrees                |
| Cab Yaw Angle   | 0 Degrees                  | 0 Degrees                  | 0 Degrees                |
| Impact Location | Left Side                  | Right Side                 | Top                      |



Front View of Cab



Rear View of Cab

Figure 8: Series 2 Test I Setup

A second set of tests were conducted using an equivalent L-series truck cab fitted with external ROPS system and subjected to the same test conditions as the production cab. The ROPS system was fabricated primarily out of 4 x 4 inch (10.2 x 10.2 cm) and 4 x 8 inch (10.2 x 20.4 cm) square tubing with a 0.375 inch (0.95 cm) wall thickness and was based on a design purchased from ROPS PTY [22] which is a commercially available design from Australia. The ROPS framework attaches behind the cab to the truck's chassis frame and extends above the cab roof and forward over the occupant space, see Figure 9.



Figure 9: ROPS Installation

## TEST RESULTS

### Series 1

Post-test roof crush profiles were generated with total station laser measurements and the residual static crush measured at the A-pillar top is presented in Table 3. As expected, the A-pillar intrusion in

the production cab test exceeded the 35.5 inches (90.2 cm) of residual crush observed in the subject accident truck cab.

Table 3: Test Series 1 Results

| Test Parameter                              | Production Cab             | Reinforced Cab             |
|---|----------------------------|----------------------------|
| Driver Side A-Pillar Resultant Displacement | 42.8 in<br>(108.7 cm)      | 7.8 in<br>(19.8 cm)        |
| Driver Side A-Pillar Vertical Displacement  | 30.7 in<br>(78.0 cm)       | 5.4 in<br>(13.7 cm)        |
| Impact Force                                | 49,555 lb<br>(220.4 kN)    | 39,878 lb<br>(177.4 kN)    |
| Energy                                      | 58,184 ft-lb<br>(78,887 J) | 40,365 ft-lb<br>(54,728 J) |
| Velocity                                    | 18.65 mph<br>(30.0 kph)    | 15.54 mph<br>(25.0 kph)    |

In Test A, the production truck cab deformed in a manner that allowed the A-pillar/header junction to contact the upper seatback of the driver’s side seat and drove the steering wheel column rearward and down onto the seat cushion. During the impact, the fiberglass driver’s side door unlatched and fractured, allowing it to separate from the truck cab. The upper portion of the driver’s side B-pillar and side header separated at their connecting seam, see Figure 10.

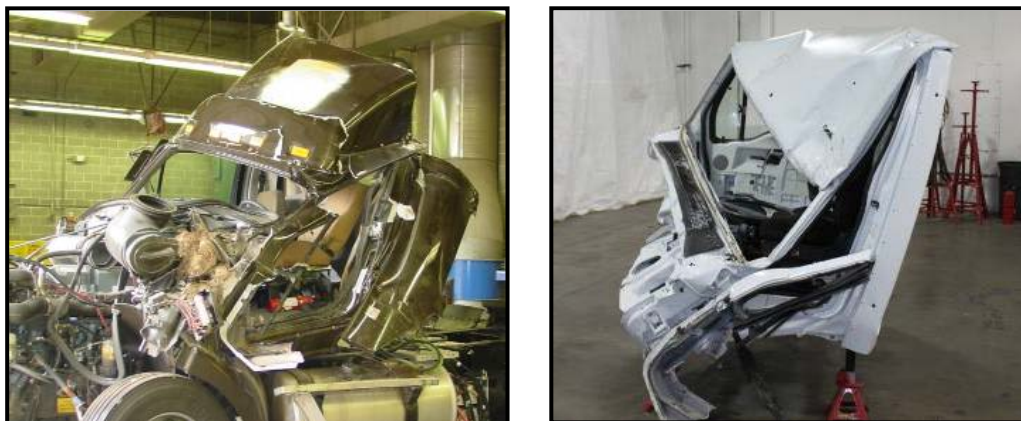


Figure 10: Accident and Test Vehicle Comparison

In order to determine the impact speed and energy for the reinforced test, the amount of energy required to produce the 35.5 inches (90.2 cm) of residual crush, as seen in the accident vehicle, needed to be determined. The production test vehicle crushed 42.8 inches (108.7 cm) statically from an energy input of approximately 58,184 ft-lb (78,887 J) and had a dynamic overshoot of 3.4%. By double integrating the sled accelerometers, the energy and displacement time histories were generated for this test. Using the same dynamic overshoot factor, it was determined that 40,000 ft-lb (54,233 J) of energy would have yielded 35.5 inches (90.2 cm) of static crush. Therefore, the reinforced test, Test B, was run at a sled impact energy of approximately 40,000 ft-lb (54,233 J) in order to compare cab roof deformation between the reinforced test cab and the subject accident cab at the same impact energy level. The reinforced cab experienced a 78% reduction in roof deformation when subjected to the impact energy required to generate the damage measured on the accident vehicle, see Figure 11. Unlike in the case of the real world accident, the reinforced roof test vehicle retained the occupant survival space, see Figure 12.





Video Still of Production Cab Deformation  
(35.5 in (90.2 cm) of A-pillar Displacement)



Reinforced Cab Post Test

Figure 11: Roof Intrusion Comparison

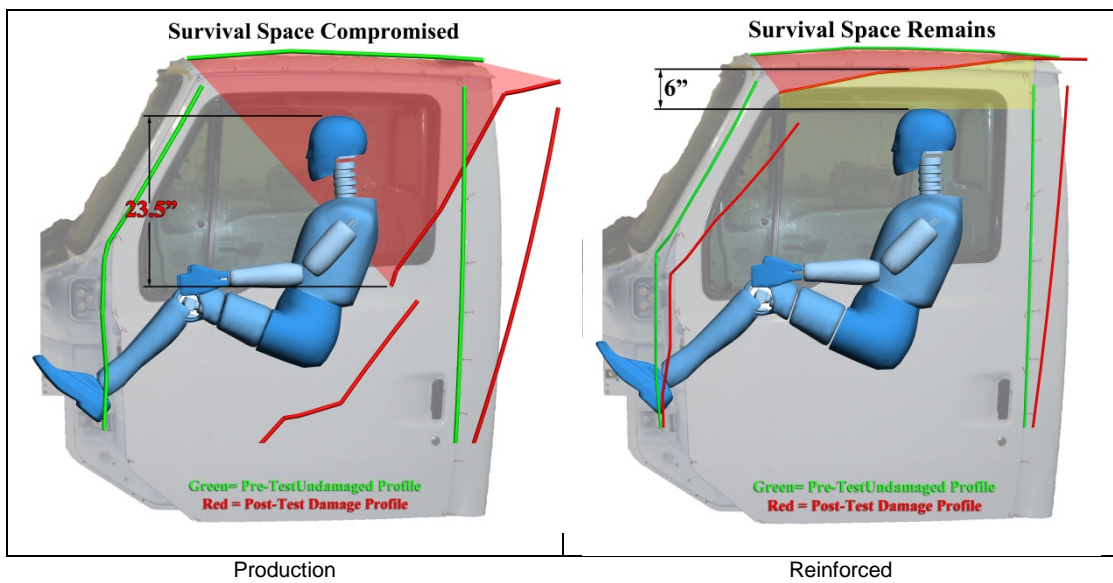


Figure 12: Survival Space Comparison

## Series 2

In the production test, significant intrusion into the cab occurred during the first test, and the subsequent tests substantially increased the level of intrusion. After being subjected to the series of three sled impacts, the cab sustained numerous structural failures and collapses and severely compromised the occupant survival space. The tested cab had a damage profile consistent with the real world accident vehicle; see Figure 13 and Table 4.



Production Cab



Accident Vehicle Cab

Figure 13: Post Test Series 2 Cab Comparison

In the ROPS equipped cab testing, the ROPS system prevented the impact sled from contacting the cab structure and prevented any intrusion of the cab for all three tests.

Each truck cab was surveyed after each test in order to measure any roof deformation. Below is a summary of the cumulative A-pillar and B-pillar deformation of the production truck cab after all three tests. For the ROPS equipped cab, the deformation of the ROPS system itself is provided below since there was no cab deformation and the occupant survival space was completely retained. Figures 14 and 15 depict the deformation to the cab and ROPS after the test series was completed.

Table 4: Test Series 2 Results

| Resultant Displacements | Production Cab       | Accident Vehicle     | ROPS                |
|-------------------------|----------------------|----------------------|---------------------|
| Driver A-Pillar         | 21.4 in<br>(54.4 cm) | 24.0 in<br>(61.0 cm) | 0.6 in<br>(1.5 cm)  |
| Driver B-Pillar         | 14.7 in<br>(37.3 cm) | 20.6 in<br>(52.3 cm) | 0.0 in<br>(0.0 cm)  |
| Passenger A-Pillar      | 30.5 in<br>(77.5 cm) | 36.6 in<br>(92.7 cm) | 4.3 in<br>(10.9 cm) |



Production Cab



Reinforced Cab

Figure 14: Post Test Series Cab Comparison

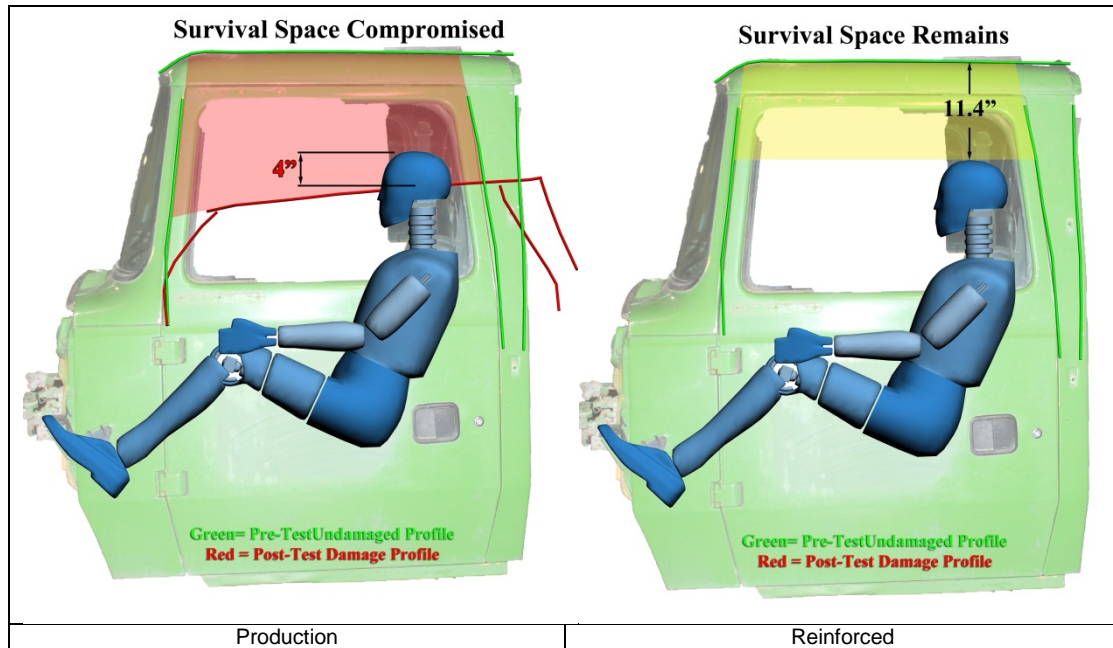


Figure 15: Survival Space Comparison

## DISCUSSION

### Reinforcement Methods

The presented testing provides analysis of two possible structural reinforcement methodologies, integral and external, to increase the strength and rollover performance for heavy truck occupant compartment cab structures.

#### *Integral Reinforcements*

The first type of reinforcement utilized in Test Series 1 is an example of an integral reinforcement. Typically, this type of reinforcement involves adding material to the inside of or adjacent to an existing structure without changing the exterior profile of the vehicle or cab. Integral reinforcements are analogous to a stronger production cab which can be manufactured by the various OEMs. In Test Series 1, the strength and rigidity of the structure was increased by inserting tubular and sheet metal steel reinforcements with foam filling inside the existing cab structure and compartment trim.

#### *External Reinforcements*

The second structural reinforcement methodology, presented in Test Series 2 involves a rollover protection system, or ROPS, and is an example of an external reinforcement. ROPS are externally mounted, rigid cage-like structures that are designed to protect the occupant compartment in rollovers by limiting vehicle structure intrusion into the occupant's survival space. These reinforcements can be utilized on existing heavy trucks with weaker roof structures. Many companies in Australia provide ROPS for heavy truck vehicles, such as ROPS Pty. Ltd. [23] and QMW Industries [24] as shown in Figure 16. These designs mount to the truck frame and extend up and over the truck's occupant compartment.





ROPS Pty. Ltd.



QMW Industries

Figure 16: Photographs of Heavy Truck ROPS Designs

These are just two of many possible reinforcement methods for this type of structure. There is a need for these methods in order to reduce heavy truck rollover fatalities and injuries by reducing intrusion into the occupant survival space.

Finally, Test 2 involved a water tank truck which had a water tank sitting well below the top of the truck cab. In the event of a rollover, the truck cab would not necessarily receive much structural support from the water tank until the cab had crush down to the height of the water tank, as seen in the accident vehicle from Test Series 2. If the tank were built higher, or above the top of the truck cab, it could act as a significant structural support during a rollover and potentially reduce the amount of cab crush similar to what ROPS structure does. The effect of a higher water tank on the vehicle's center of gravity height and vehicle dynamics would have to be considered as part of the overall vehicle design.

### Sled Test Methodology

The impact sled testing methodology outlined above was designed to analyze the crash forces and energy levels of real world truck accident cabs. With a known energy dissipation requirement, different reinforcement methods could be tested to insure the retention of adequate survival space.

Test Series 1 analyzed a 90° rollover accident which included a frictional loading component as the cab furrowed into the dirt following the tipover portion of the accident before interacting with a roadside slope. Since only one side of the cab was loaded during the accident, the impact sled barrier face was oriented to simulate the crash loading in a single test. Since the energy level required to generate the cab deformation observed in the subject accident truck was unknown, the sled impact test was developed to overshoot the energy level and corresponding cab deformation of the subject accident truck cab. The test data and high speed videos were then analyzed to determine the point at which the roof intrusion level most closely corresponded to that of the subject accident cab when accounting for structural restitution. The accelerometer data was integrated into a velocity data channel and used to determine the sled delta-V and energy imparted to the cab structure at this point in the test.

By determining the energy level of the subject accident, it was then possible to determine how an alternative cab design would perform under similar conditions. The reinforced cab sustained significantly reduced deformation and maintained the occupant compartment's survival space.

Test Series 2 analyzed a rollover accident in which a truck rotated beyond the ½ roll position, loading both sides of the cab structure. A single sled impact test cannot replicate double sided loading conditions, so multiple sled impacts were required. The approach in this test series was to generate the deformation observed in the subject truck cab through a series of multiple sled impacts. The sled

speed and cab orientation were adjusted for each test in order to generate the deformation observed in the subject accident cab.

The SAE applied a similar testing approach in the development of the J2422 and J2423 recommended practices. SAE J2422, “Cab Roof Strength Evaluation – Quasi-Static Loading Heavy Trucks”, incorporates two tests to a cab structure. The first, pre-load, impact is with the cab set at 20° of roll and has an energy requirement based on the energy to tip the cab from its static stability position to a rest position on its side and is capped at a maximum of 13,000 ft-lb (17,626 J). The second impact is a vertical impact to the entire top of the cab structure with a load requirement based on the maximum rated capacity of the front axle subject to a maximum of 22,046 lb (98,061 N). After the dynamic pre-loading impact and the quasi-static roof loading, the cab must retain a survival space allowing accommodation of the manikin defined in ECE Regulation 29. At the time SAE J2422 was issued, 01/1998, SAE also issued standard J2423, “Cab Roof Strength Evaluation – Dynamic Loading Heavy Trucks”. The only difference between the two standards was the change from quasi-static to dynamic loading for the second, vertical loading test. However, SAE J2423 does not have a recommendation or guidance for the energy of the dynamic test. SAE J2423 was cancelled in January 2004.

In the development of SAE J2422 and J2423, a series of tests on several similar heavy truck cabs was conducted [25]. The development test series resulted in cumulative energies of 42,750 ft-lb (57,975 J) and 39,550 ft-lb (53,636 J) for the quasi-static and dynamic tests, respectively. It was noted that at these energy levels the total amount of crush was less than most of the 180° rollover accidents studied.

A study by UMTRI [25] examined the forces and energies that a cab would need to dissipate in order to retain occupant survival space. The study analyzed a range of rollover configurations assuming 12 in (30.5 cm) of allowable crush with a tractor weighing 22,046 lb (10,000 kg) and with a moment of inertia of 142,382 lb ft<sup>2</sup> (6,000 kg m<sup>2</sup>). The study concluded that 38,445 ft-lb (52,125 J) would need to be dissipated. With the assumed allowable crush, the required strength was found to be 39,000 lb (180,000 N).

Both of these previous studies [25, 26] predict a higher force and energy requirement than is currently called out in the various standards even though one of the references is given as a basis for J2422 and the cancelled J2423.

The presented work also found the energy and loading requirements given in SAE J2422 to be insufficient to produce real world deformation seen in many accidents. It should be noted that with the quasi-static roof loading in this recommended practice if the peak load is reached quickly without significant roof deformation, the energy absorption of the cab and the effects of greater deformation on the structure may never need to be examined. This is inconsistent with real world accidents.

For a 90° type rollover as tested in Series 1, analysis showed that approximately 40,000 ft-lb (54,233 J) was necessary to create the deformation seen in the accident vehicle. This load level is much higher than the maximum pre-test energy level of 13,000 ft-lb (17,626 J) presented in SAE J2422. As noted in the development of this recommend practice, the energy in the pre load test is a lower bound to what would be seen in a real world accident.

For a 180° or greater rollover as tested in Series 2, three impacts with a cumulative energy of 51,500 ft lb (69,825 J) were needed to approximate the deformation from a real world accident case study. This energy level is similar to the cumulative energy levels noted to occur in the real world 180 degree rollover accidents analyzed during the development of SAE J2422. However, as mentioned previously, the quasi-static vertical testing portion of SAE J2422 simply requires a peak roof crush resistance force and has no energy requirement. These results clearly indicate a deficiency in the current recommended practices for cab roof strength and energy absorption capability.

The sled testing methodology provides a very effective way to analyze heavy truck rollovers. The impact sled generated the same type of deformation observed in a real world rollover accident and



allowed for an analysis of the energy level imparted to the cab during the subject accident. It also made it possible to evaluate the performance of alternative designs under similar test conditions.

The sled testing methodology presented in this paper will be applied in future testing to evaluate more real world heavy truck rollover accidents and the efficacy of alternative cab structures under these conditions. It is hoped that this testing can be used to develop a more advanced understanding of the forces and energy levels involved in heavy truck rollovers and to establish the strength level a cab must provide in order to protect truck occupants in rollover events.

## CONCLUSIONS

- The sled impact test methodology presented here allows for varying energy levels and impact orientations that can generate damage profiles consistent with real world accidents.
- Research by UMTRI and SAE, as well as the testing presented here, indicates that energy inputs of approximately 40,000 – 50,000 ft-lbs (54,233 – 67,791 J) are required to generate cab damage consistent with some real world heavy truck rollovers.
- There are currently no federal standards regulating heavy truck cab strength or crashworthiness in the United States. Test procedures such as SAE J2422 and ECE 29 do not require the energy levels adequate to maintain survival space in many real world rollover crashes.
- Two reinforcement methods have been shown to be capable of mitigating or managing energy inputs up to 40,000-50,000 ft-lbs (67,791 J) while maintaining occupant survival space.
- There are no technological feasibility impediments to constructing cab structures with sufficient strength to retain occupant survival space in real world accidents and to dissipate the energy levels seen in this and other studies.

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