Test Methods for Occupant Safety in Heavy Truck Rollovers

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Abstract Recent United States Federal Motor Vehicle Safety Standards (FMVSS) have focused on rollover injury mitigation of passenger cars through vehicle stability control, improving roof structure strength requirements and occupant containment; however rollovers continue to be the most dangerous accident mode for heavy truck occupants when compared to other accident modes. Despite decades of recognition of this problem, there has yet to be any mandated standards dealing with heavy truck rollover safety. Damage to heavy truck roofs can occur from lateral loading as the vehicle rolls onto its side, vertical cab loading from friction while the vehicle is on its side as well as lateral and vertical loading as the vehicle rolls onto its roof. Throughout the rollover, there can be significant longitudinal cab loading due to the longitudinal component of the roof-to-ground impact as well as friction along the ground. In the presented paper, a real-world heavy truck rollover accident is analyzed. The rollover resulted in a large degree of downward and rearward deformation about the cab floor. In the process of analyzing this rollover accident, the standard industry testing practices were considered as tools to reproduce this real world damage pattern but were ultimately deemed insufficient at inducing the type of crush necessary to match it.

In this paper, the authors present a new alternative testing method based on existing testing methodologies to evaluate heavy truck structural performance under the cab loading conditions which produce the rearward and downward cab damage pattern. For the heavy truck rollover accident study, a parametric test series was conducted. A production test was conducted to evaluate the cab strength and energy management under the subject load path. This test quantified the ability of the cab to resist deformation and the effect on the resultant residual survival space. Based on the results of this production test an alternative design cab was constructed using standard industry accepted reinforcing techniques. This alternative design cab was tested under identical conditions to evaluate the ability of the reinforcements to mitigate the degree of cab deformation and to maintain adequate residual survival space. These laboratory tests help to establish the force and energy levels of the selected rollover accident and demonstrate that alternative cab designs can significantly reduce roof crush and enhance survival space preservation under identical test conditions.

Keywords Heavy Truck, Occupant Safety, Real World Accidents, Rollovers, Test Methods

I. 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.

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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 addition, a 2009 paper analyzes the lack of rollover crashworthiness in many commercial truck designs with intrusion into the tractor's survival space leading to mechanical or crushing injury and facilitating ejection. The authors opine that "insufficient survival space during rollover accidents is the primary cause of death for drivers of large trucks" [5].

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 [6]. 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 rollover evaluation of cars and heavy trucks [7] see Fig. 1. Franchini describes that that if the contact is concentrated on the roof side edge, as is commonly seen in heavy truck rollovers of only 90 degrees roll, "pillars bend sidewise and the entire portion of the passenger compartment above the belt line deforms like an articulated parallelogram, hinged at the pillar bases" [8]. The 1986 NHTSA "Truck Occupant Protection" report suggested that improved cab designs providing survival space would improve occupant protection and illustrates the survival space concept as shown in Fig. 2 [9].

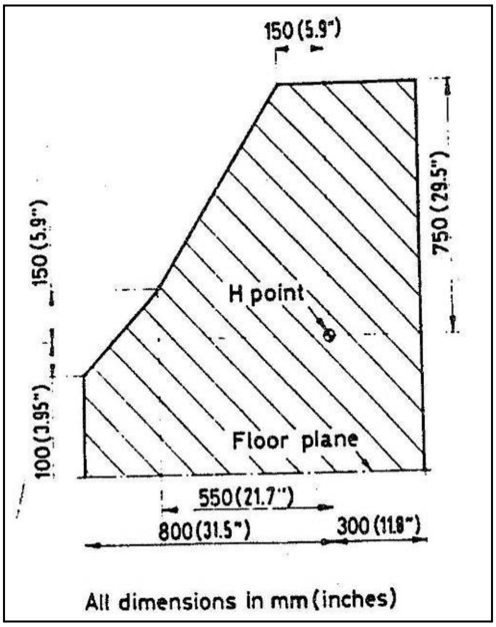

Fig. 1. 1969 "Survival Space in Trucks" [7]

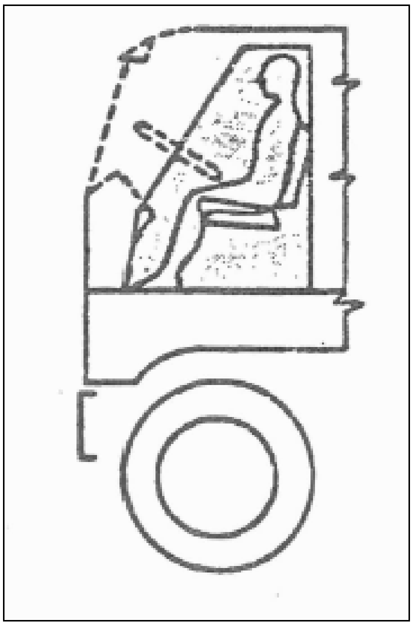

Fig. 2. Hypothetical Occupant Survival Space Needed in a Heavy Truck

Based on heavy truck data collected from 1996 to 1999, NHTSA states that "over 64 percent of the single-vehicle occupant fatalities occurred in crashes with a rollover"; approximately two-thirds of all fatalities occur in rollover crashes [10]. These statistics make clear that heavy trucks have high propensity for occupant injury in rollover and that additional design considerations, particularly structural maintenance of adequate occupant survival space, need to be made for heavy trucks in the rollover accident mode.

Previous studies by Berg (1997) [11] and Simon (2001) [12] indicate the probability of a serious or fatal injury is increased by approximately a factor of 5 by cab intrusion.

A 2003 UMTRI study [13] stated, "Rollovers represent the most severe of the various types of truck crush accounting for approximately 63% of fatal or A injuries to truck occupants. The highest priority in any crash and particularly in rollover type crashes is retention of the occupant in the cab along with maintaining sufficient survival space.” It was also conservatively estimated that a 23% reduction in fatalities was possible if cab structural integrity can be improved sufficiently to prevent crush in rollover and can also reduce severe injuries.

A number of recent studies have focused on this heavy truck accident occurrence and the possible vehicle design/crashworthiness and crash avoidance and occupant protection technology countermeasures. NHTSA has identified stronger cab structures in order to provide adequate occupant survival space, the use of stronger doors and side inflatable tubular structures to prevent ejection as well as more forgiving interior surfaces along with airbags and seat belts as possible means of reducing occupant injury [14]. Further, the U.S. Government is analyzing the need for crashworthiness standards on commercial motor vehicles with a gross vehicle weight rating or gross vehicle weight (GVW) of at least 26,001 pounds (11,794 kg) involved in interstate commerce, including an evaluation of the need for roof strength, pillar strength, air bags, and other occupant protections standards, and frontal and back wall standards [15].

The studies discussed above all point to rollovers as one of the leading causes of harm to heavy truck occupants and suggest the preservation of occupant survival space can help better protect occupants in heavy truck rollover crashes. Testing methods that simulate the forces and energy of real world heavy truck rollovers are a useful tool for the evaluation and development of cab structures that can more effectively preserve occupant survival space. This paper analyses a specific load path and cab deformation pattern which is downward and rearward parallelogramming about the cab floor. Existing test methods are considered for their applicability to this load path. This paper presents a testing method which was developed in the process of analyzing a specific heavy truck rollover accident which experienced this rearward and downward parallelogramming deformation pattern. This test provides information on the forces and energy imparted during this type of rollover cab loading event based on a comparison to the cab deformation measured in the accident vehicle. An alternative cab structure design is also tested under the same conditions in order to evaluate roof crush resistance and the potential for the increased preservation of the occupant survival space.

II. METHODS

United Nations Economic Commission for Europe (ECE) Regulation 29, implemented in 1974, lays out uniform provisions for commercial vehicles, including heavy trucks [16]. 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.

In 1998, Society of Automotive Engineers (SAE) developed a recommended practice, SAE J2422, to evaluate heavy truck cab roof strength resistance in a 180-degree rollover [17]. This procedure, revised in 2003 and 2010, 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-face of an impact sled or pendulum to the truck cab’s roof. 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. The SAE did not specify a vertical load when the recommended practice was initially published in 1998. However, in the 2003 revision, the SAE adopted the requirement of the Regulation 29 test, 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.

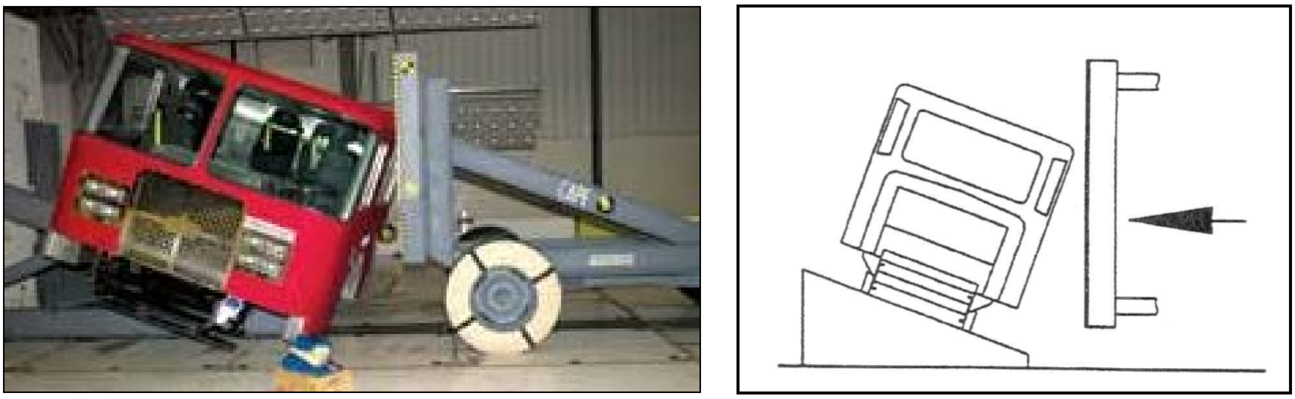

Fig. 3. J2422 Sled Impact

The Swedish Impact Tests is a heavy truck test method that has been used by Volvo since 1959 to test their heavy truck cabs ability to withstand rollovers [18]. 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) with 22,000 ft-lbs (29,400 J) of energy. 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.

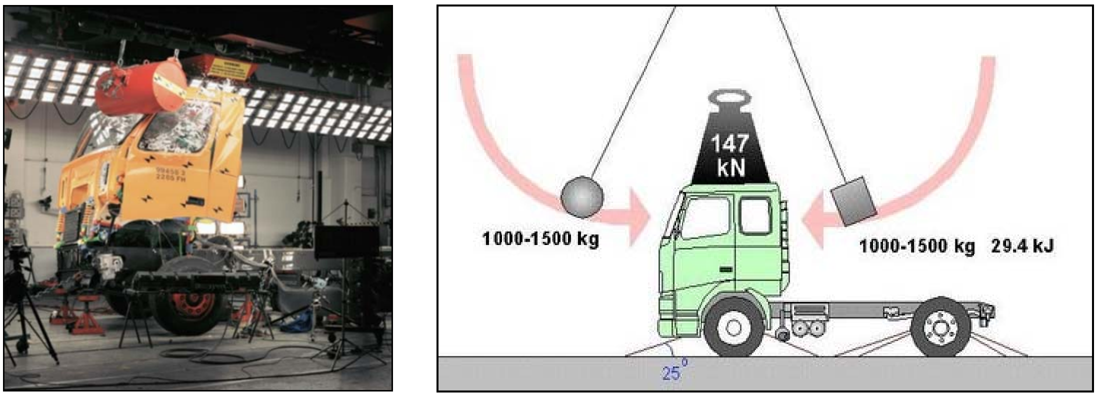

Fig. 4. Swedish Test

As with all testing, these tests each have their own limitations. One significant limitation common to all three tests is the use of a quasi-static vertical load applied uniformly to the cab's roof which loads all the pillars simultaneously. This loading mechanism may be consistent with a vehicle at rest on its roof, but does not represent the dynamic loads of a real world rollover in which one side or even one corner of the cab structure can be subjected to multi-directional loading. Under the idealized conditions of quasi-static vertical loading, the structural members of the cab are aligned with the axis of the load making it possible to generate extremely high force levels. When the axis of load application is rotated away from the vertical axis of the cab, as it might be in a real world rollover accident, the load is concentrated on a smaller portion of the cab structure and is out of alignment with the cab's structural components. The quasi-static vertical loading specified in the above test procedures is less demanding of the cab structure than the dynamic, multi-axial loading known to occur in many rollovers.

It is not possible to consistently reproduce the dynamically varying loads that can be generated in a real world rollover accident sequence. However, a test methodology can represent the overall forces and energy applied during a rollover crash. The SAE J2422 test procedure attempts to replicate the lateral-to-vertical loading sequence of a rollover accident by combining a dynamic test with a quasi-static test. The initial dynamic lateral sled impact is intended to simulate the tipover portion of the roll and to compromise the cab structure. The subsequent static vertical load application is intended to simulate the loading generated during the inverted portion of the rollover. The SAE J2422 initial sled impact however has a significant shortcoming. The test protocol requires that the cab be tested as it would be mounted to its frame using the factory frame mounts. These factory frame mounts are essentially a cab suspension system designed to isolate the cab and driver from the road. This requires the frame mounts to be extremely compliant. During development of the J2422 test procedure, the SAE conducted full scale tractor tipover testing and determined that 25,000 ft lbs (33,895 J) of energy would generate damage comparable to real world 90° rollover accidents. However, during the sled test protocol development, sled impacts at this energy level resulted in minimal cab deformation. The energy was instead creating significant cab floor and frame mount damage which did not occur in the full scale tip over tests. The SAE determined the behavior of the cab mounts under the conditions of the sled impact testing was not consistent with real world rollovers. However, the problem was addressed not by eliminating the cab mounts and their significant compliance, but by lowering the applied sled impact energy to 13,000 ft lbs (17,626 J). This successfully eliminated the cab mount failures, but meant that the cabs were experiencing only about half of the energy level determined to be sufficient to represent a 90° rollover.

REAL WORLD ACCIDENTS

A real world heavy truck accident was investigated in which the driver was severely injured and the cab structure was seriously compromised. In this accident, the heavy truck equipped with a fuel tanker exited a paved road surface to the right, traveling on the grassy shoulder adjacent to the roadway. The heavy truck then turned back towards the roadway, causing it to roll passenger's side leading one complete revolution. The accident vehicle is shown in Fig. 5.

Fig. 5. Investigated Field Accident Vehicle

During the investigated accident, the driver and sole occupant received incapacitating head and spinal injuries. The residual crush relative to the driver's seating position is shown in Fig. 6 & Fig. 7.

Fig. 6. Driver's Seating Position

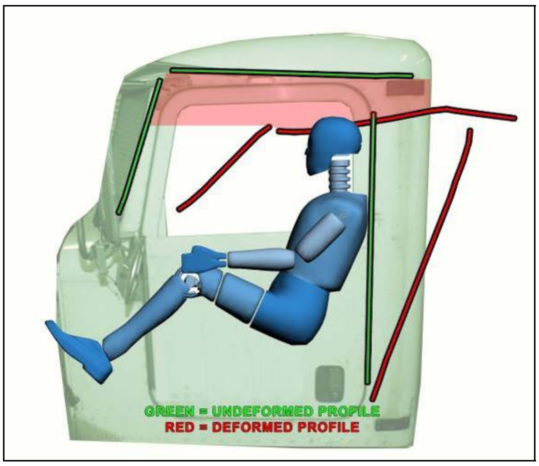

Fig. 7.Residual Crush

The investigated accident has a damage pattern that is consistent with other real world crashes investigated by the authors, shown in Fig. 8. This damage pattern is the predominance of rearward and downward parallelogramming of the cab about the floor. The design of heavy truck cabs provides predominately compressive load strength under vertical loading. When significant longitudinal loads are applied along with vertical loads, the cabs are subjected to a significant shear component which results a characteristic damage profile.

Fig. 8. Other Field Accidents with Similar Damage Patterns

In order to better understand the approximate forces and energy sustained by the accident cab, an impact test on an undamaged cab was conducted. None of the three aforementioned test methodologies would produce a damage pattern consistent with this accident vehicle, therefore the authors modified the existing test methodologies to impart roof loading to an exemplar cab that would approximate the cab deformation seen in the field accident studied. The intention of running an impact test on an exemplar vehicle is not to recreate the subject accident but rather gain engineering insight in the structure's load and energy capacity.

PRIOR SLED TESTING

Real world rollover accidents are complex events typically resulting in multi-directional cab deformation. Recreating this multi-directional deformation in a single test can be challenging. In particular, the deformation created by the combination of reaction forces and friction forces can be particularly difficult to recreate as these forces are often applied to a vehicle structure in significantly different orientations. The solution to this problem is generally to combine multiple tests with different load paths together to create the desired loading and deformation. A good example of this is the J2422 test which combines a dynamic angled pre-load test with a subsequent static distributed vertical load test. The authors are very familiar with this process having many times combined two or even more tests together to create a desired result. What is needed is a biaxial sled test methodology which can simultaneously generate reaction and friction loading, making it possible to simulate two loading mechanisms in a single test.

BIAXIAL SLED TESTING

A biaxial test configuration was developed in which the sled velocity vector and the platen surface are oriented at different angles. A reaction force is generated acting perpendicular to the surface of the platen. At the same time, a friction force is generated parallel to the surface of the platen resisting the sliding movement of the cab. The combined dynamic reaction force and friction force loading is applied off the vertical axis of the cab. This test configuration eliminates the need to combine multiple tests, such as a dynamic sled test and a quasi-static test to achieve the desired cab deformation pattern.

In the subject sled tests biaxial loading was achieved by mounting the truck cab onto a sled and then driving the sled into an angled impactor face. The truck cab was rigidly mounted to the sled frame in order to eliminate cab mount compliance and focus the sled impact energy on the cab structure. The large concrete impact barrier was modified by welding a large rigid steel lattice frame above and ahead of it at a 15 degree angle from horizontal as the reaction surface. In order to eliminate the compliance of the tires used on the sled carriage, skid plates were fitted to the floor and the underside of the sled. Before the test cab contacts the platen, the skid plates on the sled and the floor slide into engagement, providing rigid support to the sled carriage in the vertical axis.

Fig. 9. Biaxial Sled Test Set-Up

A series of trial tests were conducted to refine the details of the sled test and to provide an estimate of the amount of sled impact energy necessary to create the desired cab deformation. Then a production cab was subjected to the biaxial sled impact test. The resulting cab deformation was compared to the subject accident cab deformation to provide information regarding the general levels of force and energy that would have been applied to the subject accident cab, the cab strength under this loading condition and the location and types of structural damage generated in the cab.

As a result of this test, an alternative design cab was constructed. This cab was reinforced using commonly accepted industry techniques which significantly strengthened the cab and the door. These structural reinforcements included the addition of integral 4130 steel tubing for internal reinforcement and rigid polyurethane foam for the prevention of section collapse to the cab’s structure. The total weight of the reinforcements was 238.1 lbs (108 kg). This is less than 2% of the weight of the subject tractor which is in excess of 14,000 lbs (6350 kg). These modifications were simple retrofit type reinforcements made from basic components. In production, a manufacturer would be able to use CAE, FEA and normal production optimizing techniques such as steel stampings to significantly reduce this weight in the 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 Fig. 10. The reinforced truck cab was then subjected to a sled test impact to its roof identical to the production truck cab test.

Metal Cab Reinforcements Metal Door Reinforcements Foam Reinforcements

Fig. 10. Cab Reinforcement Schematics

III. RESULTS

BIAXIAL SLED TESTING

The production sled test cab sustained significant rearward and downward parallelogramming consistent with the subject accident vehicle cab. Both door hinge pillars & both A-pillars rotated rearward and downward about the floor. Both side headers rotated rearward and downward about the B-pillar tops. The rear bulkhead and B-pillar/post assemblies rotated rearward and downward about the floor. The driver's door opened. The windshield and large passenger's door window fractured during the test. All other glazing remained intact, see Fig. 11.

Fig. 11. Accident and Test Cab Comparison

The reinforced test cab sustained minimal intrusion into the occupant compartment, see Fig. 12.

Fig. 12. Production and Reinforced Test Cab Comparison

Post-test roof crush profiles were generated with Faro arm measurements and the residual static crush measured at the A-pillar top is presented in Table 1. The A-pillar deformation in the production cab sled test closely matched the deformation observed in the subject accident truck cab. The static resultant A-pillar deformation of the test cab was within 13% of the accident vehicle, and the static vertical A-pillar deformation of the test cab matched the accident vehicle exactly. The biaxial sled test successfully generated the downward deformation associated with reaction force loading and the rearward deformation associated with frictional loading. The 19 inches (48.3 cm) of static A-pillar resultant crush generated in the production test was reduced to 4.5 inches (11.4 cm) in the reinforced cab.

Table 1: Sled Test Results

Test Parameter	Accident Cab	Production Cab	Reinforced Cab
Driver Side A-Pillar Resultant Displacement	19.0 in (48.3 cm)	21.4 in (54.4 cm)	4.5 in (11.4 cm)
Driver Side A-Pillar Vertical Displacement	9.0 in (22.9 cm)	9.0 in (22.9 cm)	1.4 in (3.6 cm)
Energy	~45,000 ft-lbs (61,012 J)	~45,000 ft-lb (61,012 J)	~45,000 ft-lb (61,012 J)

IV. DISCUSSION

The impact sled testing methodology outlined above was designed to analyze the crash forces and energy levels of real world truck accident cabs. The biaxial sled testing methodology was developed to simulate the combination of reaction force and friction force loading that occurred in the subject accident. The platen was oriented 15 degrees off the horizontal axis of the test cab, generating a primarily downward normal force relative to the cab. However, the sled translated the cab off axis from the surface of the platen. The angle between the velocity vector of the cab and the surface of the platen generated a frictional loading component in addition to the reaction force. The addition of the frictional loading component allowed the sled test to simulate biaxial loading of the cab structure.

This testing methodology provided valuable insight into the forces and energy needed to produce the crush patterns observed in the subject real world rollover accident. The test demonstrated that catastrophic cab damage consistent with the combined reaction force and friction force loading components of the selected real world crash can be generated with energy levels of approximately 45,000 ft-lbs (61,012 J) of energy. The alternative design sled test produced significantly reduced cab deformation and demonstrates the potential for maintaining an increased level of occupant survival space.

V. CONCLUSIONS

Investigation into a real world heavy truck rollover accident was conducted involving a restrained occupant who was seriously injured. Factors to be considered in the analysis of this accident were the severity of the accident (energy and force levels experienced), the degree of cab deformation under those levels of force and energy.

Biaxial sled impact testing was conducted on a production cab which generated cab deformation and structural damage consistent with the subject real world heavy truck rollover accident cab. At this level of cab deformation the residual survival space for the occupant of the subject accident vehicle was dramatically reduced. The impact energy required to create this level of cab deformation was approximately 45,000 ft-lbs (61,012 J). Considering the potential energy of the subject accident, this is a small fraction of the available energy.

Biaxial sled impact testing was conducted on a structurally reinforced cab subjected to the same test conditions and impact energy which demonstrated a dramatic reduction in cab deformation. These reinforcements were able to reduce cab deformation by almost 80%. The weight of these modifications in a simple retrofit configuration which was not optimized was just 238 lbs. (108.0 kg) or about 2% of the weight of the subject tractor. This additional weight could be substantially reduced through iteration and optimization of the modifications in a production design.

The biaxial testing methodology generated cab deformation that was consistent with the combination of reaction loading and frictional loading of a selected rollover accident mode. This biaxial test methodology demonstrated that sled testing can be successfully used to simulate two loading mechanisms simultaneously. By varying the cab and platen orientations used, the biaxial sled impact testing methodology presented in this paper could be used to simulate a broad range of rollover accident loading conditions under a broad range of impact energy levels. The biaxial sled impact testing methodology presented in this paper could also be used for the development of new and improved cab structural designs.

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