Proceedings of IMECE2005
2005 ASME International Mechanical Engineering Congress and Exposition
November 5-11, 2005, Orlando, Florida USA

IMECE2005-81300

EVALUATION OF HEAVY TRUCK ROLLOVER CRASHWORTHINESS

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ABSTRACT

Heavy trucks (those having a gross vehicle weight rating of greater than 10,000 pounds) are an essential part of the United States economy and account for 4% of all registered vehicles. The large size and weight of these vehicles can pose a serious safety threat to the vehicle's occupants in the event of a rollover collision. The rollover crashworthiness of heavy trucks, in particular the structural integrity of the cab, is analyzed in this paper. An actual rollover accident was analyzed and the cab design of an exemplar vehicle was evaluated. Modifications were made to the exemplar and an inverted drop test onto the roof of the cab was conducted. Recommendations for improving the rollover crashworthiness of heavy trucks are provided. An analysis of heavy truck rollover accidents was also conducted for data available from 1994-2002 by submitting queries to the Fatality Analysis Reporting System (FARS), which is administered by the National Highway Safety Administration (NHTSA), in order to determine the number of incapacitating and fatal injuries that occurred when the occupants were contained in the cab during a rollover accident. The percentage of incapacitating and fatal injuries for restrained occupants was determined by analyzing the rollover data obtained from the FARS rollover query that was used and was found to be 35%. Therefore, restrained occupants in heavy trucks can sustain significant injuries during rollover accidents, in part, due to insufficient rollover crashworthiness.

INTRODUCTION

Heavy trucks are an essential part of the transport of a vast array of commercial, industrial, and consumer products in the United States. According to the National Center for Statistics and Analysis, a division of the NHTSA, 7,857,674 heavy trucks were registered in the United States in 2001, accounting for 4 percent of all registered vehicles [1]. In 1994 that number was only 6,587,885. This indicates a dramatic increase in the number of heavy vehicles. In 2002, 434,000 large trucks were involved in traffic accidents. Of those accidents 4542 involved fatalities. This equates to one out of nine traffic fatalities being a result of an accident involving a heavy truck. Given the dramatic increase in heavy truck use as well as the large number of accidents and fatalities every year involving heavy trucks, increasing attention is being given to the study of heavy truck crashworthiness and safety.

Heavy trucks can also be involved in rollover accidents. This type of accident, as with passenger vehicles, is not as frequent as other types of accidents, but can result in significantly more damage to the vehicle and injuries to the occupants of the heavy truck.

This paper describes the rollover crashworthiness of heavy trucks and a case study is presented which includes a rollover accident and a test of a modified truck. A study of heavy truck accidents that occurred in the time period from 1994-2002 was also analyzed for this paper. The data was collected from the Fatality Analysis Reporting System (FARS), which is controlled by NHTSA [2]. The specific interest was to evaluate significant structural damage to the truck, and injuries that occurred to the restrained occupants of the large trucks during rollover accidents.

ROLLOVER CRASHWORTHINESS

In 1991, University of Michigan Transportation Research Institute (UMTRI) researchers Campbell and Sullivan reported at the 35th Stapp Car Crash Conference that about 60% of all heavy truck driver fatalities are associated with rollover accidents. They concluded from studying National Transportation Safety Board crash reports that, “Existing cab structures above the plane of the dash are not sufficient to withstand the forces produced during rollover” [3].

Several studies have been conducted to evaluate the crashworthiness of heavy trucks. Clarke and Leasure state that improving cab design to provide occupant survival space in a crash could enhance truck occupant protection [4]. In another crashworthiness study, Ranney concluded that heavy truck rollovers were the most frequent cause of truck occupant fatality and that the most frequent damage location in fatal rollovers was the top of the truck [5]. In 1978 Grattan and Hobbs of the United Kingdom conducted a study on injuries received by heavy truck occupants, from which they made the conclusion that making the cab more resistant to the crushing of its occupants could add to the protection offered by the seat belt [6].

Numerous other studies not mentioned have evaluated the injuries received during various types of heavy truck accidents. One conclusion can be drawn: insufficient survival space during rollover accidents is a primary cause of death for the drivers of large trucks; therefore, structural integrity of the cab of the heavy truck is critical to occupant safety.

CASE STUDY

Accident Summary

The driver of a 1999 Freightliner FLD heavy truck was killed as a result of the structural collapse of the tractor cab during a 180° rollover accident. This truck was pulling a trailer carrying a full load of cylindrical hydrogen tanks. The rollover was precipitated by the impact of a pick-up truck, which swerved to the left striking the Freightliner truck and disabling its right-hand steering mechanism. The Freightliner veered to the left and back to the right, eventually overturning and landing on the vehicle’s left side. The tractor and trailer slid down the roadway and started to slide onto the grassy shoulder to the right of the road. The tractor rolled onto its roof in the grass causing complete collapse of the cab that intruded into the occupant’s survival space. The truck and trailer left the road coming to rest, mostly parallel to the direction of traffic, with the trailer having crossed a driveway, and the cab resting on this driveway.

Accident Reconstruction

The accident sequence commenced when a pickup truck left the roadway and lost control upon re-entering the roadway. When the pickup truck re-entered the roadway, it crossed the right hand travel lane and collided with the semi-tractor in the left hand travel lane. The pickup truck collided with the right front corner area of the semi-tractor. This was evidenced by the damage to the right front bumper and grill area of the semi-tractor. The pick-up truck likely made multiple contacts down the right side of the semi-tractor and trailer combination. A fiberglass camper shell was dislodged from the pick-up truck and came to rest in the center of the 2 northbound lanes. Post collision, the pick-up truck exited the roadway to the right hand side. The pick-up came to rest approximately 70 feet from the edge of the right shoulder after traveling approximately 367 feet from the point of impact and rotating approximately 180 degrees.

After the impact between the semi-tractor and the pick-up truck, the semi-tractor veered to the left hand side of the roadway and then back to the right. As the semi-tractor veered back to the right, the tractor began to yaw in a clockwise rotation and the trailer also began to sideslip. The tire marks from the trailer run along the left side of the left hand shoulder but remain on the paved surface. The tire marks then begin to migrate across the roadway from left to right.

The tractor and trailer combination overturned in the middle of the roadway just after the trailer tires crossed the left hand yellow fog line. When the tractor and trailer combination overturned, the tractor was positioned over the right hand white fog line. The roll began with the driver’s side leading. Scratch marks on the driver’s side of the tractor indicate that the tractor was sliding on the pavement.

The tractor continued to roll over onto its roof as the cabs exited the roadway. The trailer remained stretched across both travel lanes while the cab was primarily on the grass along the right shoulder of the roadway. At this point the tractor and trailer combination had become perpendicular to the primary direction of traffic. The trailer continued sliding on the paved surface as it rotated in a clockwise direction. Most of the distance traveled by the tractor and trailer combination after overturning was by sliding rather than rolling as shown by the “polishing” effects on the roof of the tractor. The tractor only made ½ roll throughout the entire sequence and the trailer made approximately ¾ of a roll.

As the tractor and trailer continued sliding down the paved surface, the trailer rotated such that the rear of the trailer began to lead the tractor and trailer combination. As the trailer rotated in a clockwise direction, the rear right corner of the cab of the tractor re-entered the paved surface and was traveling in a rearward direction along the right shoulder. The trailer exited the roadway and continued to rotate in a clockwise direction. As the trailer exited the roadway, it rolled over onto the right side of the trailer. Although the trailer rotated onto its right side, it should be noted that the tractor remained mostly inverted. The rear of the trailer lead the tractor and trailer combination over a driveway (see Figure 1).

The tractor and trailer came to rest with the trailer on its right side and the rear of the trailer near the fence of a nearby field. The front of the trailer came to rest near the edge of the driveway. The tractor came to rest near the center of the driveway on its roof. The frames of the tractor and the trailer were twisted to allow the tractor to be on its roof while the trailer was mostly on its right side.

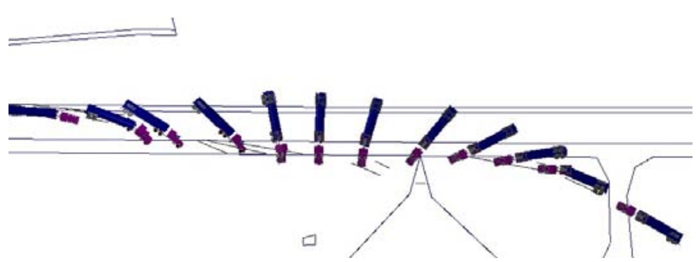

Figure 1. Diagram for tractor and trailer position.

The speed of the tractor and trailer at the point of trip was calculated to be in a range from 57 to 70 mph. The speed as the trailer exited the roadway was approximately 35 mph.

Heavy Truck Cab Performance

The cab of this vehicle was not designed to withstand a rollover collision. The cab was made almost entirely of relatively light-gauge aluminum, with only a very few pounds of steel. A survey of the panels was undertaken using a magnet, and the only steel found was in screws and some U-channel beneath the floor to provide strength and rigidity. The rivets were also made of aluminum.

An inspection of the rear of the cab gave no indication that it was forced into the dirt. There was no dirt or gravel present, and the scratch and buckling fold patterns indicated that the cab damage was from the rollover proper and matchboxing to the passenger side, not from movement on the ground in a backwards direction.

The vertical survival space as measured from the center front edge of the passenger seat was 29 ¼”. Measured at the same location on the driver’s side, there was 30” of vertical survival space (see Figure 2).

Figure 2. Photograph of the accident vehicle

Inverted Drop Testing

In order to demonstrate that this cab can be made more crashworthy relatively inexpensively and easily, a roll cage was constructed within the existing cab structure, with no modifications made to the exterior envelope of the structure (see Figure 3). The cage was constructed from 1.5” diameter DOM (drawn over mandrel) seamless tubing, 1020 plain carbon steel. The tubing was hot formed, with scale still present. Over the scale, the manufacturer printed C1020 HT39759 150016-06 in white ink. Radii were bent using an air bender, preventing local buckling. Welding was done with a MIG (metal inert gas) system using low carbon filler metal. No ancillary padding or cosmetic enhancements were applied to this demonstrative roll over protective system (ROPS).

As installed, the roll cage consisted of three inverted-U shaped hoops to provide resistance to rollover-induced forces. The first hoop was located to the rear of the A-pillar in the existing space behind the dashboard, from the floor to the ceiling. This hoop was approximately 67” wide and 58” high, and was angled from the base backwards at an approximate 8^o angle to match the rake of the dash and windshield. This reduced the headspace by approximately 2.5”, but not the functionality of the cab. The hoop endpoints were welded to ¼” mild steel plate, 6” square, that was further fastened to the floor pan using 4 bolts. A horizontal knee bar, 17.5” from the floor, further added rigidity to this hoop. The upper corners of the hoop were not gusseted, but bent at a 6” radius.

The primary occupant protection was provided by two hoops at the B-pillar location, behind the seats, with the first hoop ~28” behind the A-pillar hoop. These two hoops were separated by approximately 5”, center to center. These rear hoops attached to the front hoops by 4 symmetrically spaced horizontal members, welded at each end. A single gusset was used at the front B-pillar hoop, behind the driver’s head. It was an elbow, approximately 15” long horizontally and 12” vertically. The rearmost B-pillar hoop was welded to a 6” square plate at the bottom, while the forward hoop was welded to a 4” square plate at the bottom. Each plate was bolted to the floor pan. The plates were the only direct interface between the cab and the roll cage. Thus, above the floor pan, the cage “floated” within the vehicle. Based upon a steel density of 0.3 lbs/in^3, this cage weighed approximately 148 lbs.

This cage was deliberately not optimized; as such an exercise would have yielded no benefit for this demonstration. If a similar design were used for a production vehicle, less material could be used with the same strength and better utility for the occupants. The front hoop would be within the dashboard and windshield structure. The B-pillar hoops would remain virtually in the same place, and would not be objectionable. All hoops could be placed between the outer skin and the headliner, making them invisible to the user. Aluminum could even be used if it were thick enough and designed correctly to provide sufficient strength. Further improvements to this ROPS would include tying it directly to the structure, padding the members, designing to prevent “blind spots”, and optimizing the amount of material used. Note that this design allowed the sleeper to deform, which is not of principal concern. Any occupant in the sleeper should be in a favorable position during rollover, and will be less affected by a loss of space.

Figure 3. Photograph of the exemplar roll cage

The roll-caged exemplar vehicle was inverted using two cranes in order to suspend it in an undamaged state. It was held at rest 12 inches (30.5 cm) above the plywood that covered the concrete test surface. The lowest point of the truck was the upper corner of the A-pillar on the driver’s side. The chassis was oriented at a 24.8^o degree roll angle and a 5.5^o pitch angle, within the stated ± 0.5 tolerance given in the 25^o and 5^o angles in accordance with the SAE recommended practice J996, *Inverted Drop Test*. A quick-release mechanism was attached to ensure a “clean” drop without hesitation or energy loss. Note that the exhaust stack was cut off flush with the cab roofline prior to the inversion of the cab in order that it would not interfere with the test (see Figure 4).

Figure 4: Inverted vehicle, ready for testing.

The vehicle was dropped causing major cosmetic damage to the cab, as can be seen in Figures 5 and 6. While this cab would have to be replaced after this test, the occupant survival space is not compromised sufficient to be life threatening. Even the sleeper component, which was largely unprotected by the roll cage, was not grossly deformed during the test.

Figure 5: Exemplar roll-caged vehicle, post drop test.

Figure 6: Exemplar roll-caged vehicle, post drop test.

The impact energy imparted to the cab by this test was greater than that experienced in the rollover that is the subject of this investigation. The results of the testing indicate that the survival space described in the previously mentioned case study could have been maintained by a roll cage that was properly designed and manufactured. Such a protection system would be modestly priced, and unobtrusive to the user. The vertical loss of space was a mere 1.5", well less than the amount shown in statistical studies to be threatening to human life.

Recommendations

Good design can be used to dramatically increase roof strength with a modest increase in overall vehicle mass. A review of technical fixes was given by Herbst, et al. [7]. These technical fixes were specifically for passenger vehicles but are also relevant to heavy truck cabs. The following changes are all low-tech improvements that can be made at low cost:

1. Seam welding of intersecting stampings in which the entire intersecting lap is fused. This would replace the small resistance spot welded "buttons" or rivets.
2. Stronger steel in the form of any number of commercially available high strength low alloy (HSLA) grades. Bake-hardenable steels using precipitation-hardening mechanisms can also be employed.
3. Thicker components can be used to attain the same function as #2 above, simply by adding more metal of the same strength as the original.
4. Gussets at the roof rails and pillar intersections can dramatically increase the cross-sectional moment of inertia and the strength of the components. This also gives resistance to collapse of columns at their bases due to torque loading.
5. Channel sections can be made of closed sections rather than open to improve the strength disproportionately to the increase in mass.
6. Structural members used for safety can be left whole without holes for secondary functions (e.g., wiring, hardware mounting). Holes placed in tubular sections (present for a variety of design and manufacturing reasons) significantly weaken these tubes in bending.
7. Rigid foam is currently used for NVH (Noise, Vibration and Harshness) attenuation in many automobiles. It also can be used to prevent buckling of hollow cylinders and sections. Thin-wall segments are inherently susceptible to collapse
8. Door window frames can be made to lock securely to roof rails. This links the door to the roof, both allowing the doorframe to absorb loading, and also to prevent the door from peeling away from the roof during a rollover collision.

The quickest and most effective immediate structural fix for the weak roofs of heavy trucks would be to include an appropriately sized roll cage within the existing structure. This cage could be made of only a few pieces of mild steel tubing, which would encapsulate the primary cabin area. The Sports Car Club of America (SCCA) has established certain requirements for roll bars and roll cages for racecars. The SCCA requires that roll bars or roll cages be constructed out of the mild steel alloys SAE 1010, 1020, or 1025 or the higher strength chrome-moly alloys SAE 4125 or 4130. The higher strength alloy can be made in thinner sections but it is more difficult to weld than is mild steel. Within the "rally car" races, rollovers are somewhat common, while injuries are very uncommon.

The long term solution for heavy trucks is to incorporate a roll cage as part of the overall cab structure, optimizing the amount of material and its geometry to provide critical protection to drivers and passengers during rollover. This can be done quickly and inexpensively.

ANALYSIS OF HEAVY TRUCK ROLLOVER DATA

Data Selection

Several databases exist that can be queried for specific accident data. The University of Michigan Transportation Research Institute compiles statistical data for heavy trucks; however, they do not provide the specific data that was of interest in this study. The FARS database was chosen because of the high specificity that can be used in developing a query. The data of greatest interest was that which could be used to determine the injuries of large truck occupants during a rollover accident. The specific data of interest is described in the abstract of this paper. The chosen delimiters could be selected to create a query for the FARS database.

Data Analysis

All heavy truck accidents were first evaluated and then the previously stated rollover query was used. From a comparison of these two queries, the percentage of fatal and incapacitating accidents that correspond to the specific rollover accident in question could be determined.

Figure 7 shows the results of all accidents from 1994-2002. The number of fatal accidents per year for heavy trucks peaked in 1999 at 659. The lowest number of fatal accidents for this time period was 523, which occurred in 1996. A downward trend is apparent from 1999-2002, with only 537 fatal crashes occurring in 2002. Since this data looks at all fatal heavy truck accidents, the number of vehicles and persons involved are somewhat higher every year than the number of fatal accidents.

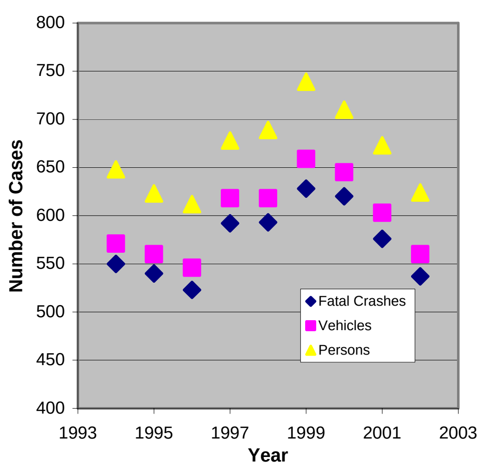

Figure 7. FARS data for all fatal and incapacitating heavy truck crashes from 1994-2002.

The rollover query was then submitted to the FARS database and the number of accidents that met the requirements of this query is shown in Figure 8. The average percent of fatalities and incapacitating injuries, which matched the rollover query, was 18%, with a high in 2002 of 21% and a low of 17% occurring in 1994, 1995, and 1997. Therefore, on average, 18% of all heavy truck incapacitating and fatal injuries were a result of a single vehicle rollover accident where the rollover was the most harmful event, either the first or subsequent event with contained occupants receiving fatal or incapacitating injuries and the truck receiving severe and disabling damage. This is a very high percentage given such a specific type of accident.

The rollover data shown in Figure 8 shows some similar trends as the data for all heavy truck accidents shown in Figure 7. The highest number of fatal and incapacitating crashes, 126, occurred in 1998, with the lowest number of crashes, 93, being reported in 1993. A downward trend from 1998 to 2001 is seen, but in 2002 the number of crashes rose slightly from 107 in 2001 to 115 in 2002.

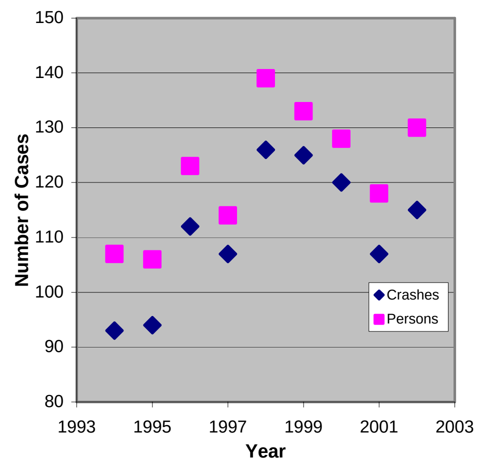

Figure 8. FARS data for heavy truck rollover accidents from 1994-2002 that meet the described query.

The results from the rollover query were further analyzed to determine the restraint use for these accidents. Table 1 shows the findings of this analysis. The average known restraint use during the 1994-2002 time period was almost 35% per year. The conclusion can be made from this data analysis that, on average, over 6% per year of all heavy truck fatalities and incapacitating injuries were restrained occupants in rollover accidents per the previously mentioned query.

Table 1.
Total fatalities and incapacitating injuries and percentage restrained in rollover accidents

Year	Total Incapacitated and Fatally Injured	Total Restrained Fatalities and Incapacitating Injuries	Percentage Restrained
1994	107	31	29.0
1995	106	35	33.0
1996	123	41	33.3
1997	114	44	38.6
1998	139	37	26.6
1999	133	48	36.1
2000	128	50	39.1
2001	118	44	37.3
2002	128	48	37.5

The overall conclusion from this data is that over 6% of the heavy truck incapacitating injuries and fatalities occur as a result of restrained occupants being killed or incapacitated from the severe or disabling deformation that occurs to the truck during a rollover accident.

CONCLUSIONS

Heavy trucks can be involved in rollover accidents and receive significant damage to the cab structure. In such instances, as was seen in the case study, significant injuries can occur when the survival space is compromised to a large degree. The testing that was presented showed a possible recommendation to strengthening the roof structures by adding a roll cage.

The FARS database was queried and data gathered for large truck rollover accidents. A specific query was designed to include rollover accidents of heavy trucks where the rollover was the most harmful event; the rollover was either the first or subsequent event; the truck received severe and disabling deformation; the occupants were not ejected; and the injuries sustained were either incapacitating or fatal. This rollover accident data was also compared with the total number of heavy truck accidents where incapacitating or fatal injuries occurred as reported by FARS for the 1994-2002 time period. This data was also then analyzed for restraint use. The following conclusions were made from this data analysis and review of a case study:

1. As stated by Campbell and Sullivan [3] and as was seen from the case study, “Existing cab structures above the plane of the dash are not sufficient to withstand the forces produced during rollover.”
2. Several techniques could be used to increase the rollover crashworthiness of heavy truck cabs, one of which being the addition of a roll cage.
3. The average percent of persons involved in accidents, which matched the rollover query, was 18%, with a high in 2002 of 21% and a low of 17% occurring in 1994, 1995, and 1997.
4. The percentage of incapacitating and fatal injuries for restrained occupants was determined by analyzing the rollover data obtained from the FARS query and was found to be 35%.
5. The overall conclusion from this data is that over 6% of the heavy truck fatalities occur as a result of restrained occupants being killed or incapacitated from the severe or disabling deformation that occurs to the truck during rollover accidents.

ACKNOWLEDGMENTS

The authors would like to thank The Engineering Institute and Eliseco Systems for their support and assistance in the completion of this work.

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