A FRAMEWORK FOR IMPROVING OF HEAVY TRUCK CAB CRASHWORTHINESS UNDER ROLLOVER CONDITIONS

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ABSTRACT

In 2012 the US Congress directed the Federal Motor Carrier Safety Administration (FMCSA) to improve commercial motor vehicle safety through the MAP-21 Act. NHTSA reported to the US Congress in 2015 that heavy truck rollover crashworthiness should be improved. To that end NHTSA sent a letter to the president of SAE asking if improvements in test methods could be suggested that would result in improvement of rollover performance. In this study we review the performance of heavy truck cab structures that meet the requirements of J2422 and suggest a framework for improving rollover crashworthiness for heavy trucks.

INTRODUCTION

Historically, there has been significant work to support the advancement of heavy truck occupant crash protection. However, in many areas of heavy truck crashworthiness the results of these efforts have not been translated into adequate safety standards and/or test procedures. In many cases this can be attributed to the lack of coordination and planning between government, industry, and research stakeholders. This paper will outline a suggested framework for improving evidence-based heavy truck cab safety standards based on the lessons learned from previous efforts. Specific focus will be on the structural integrity of heavy truck cabs in response to rollover conditions.

The foundation for all vehicle safety improvements often lies in crash data. Heavy truck crash data have been collected in the U.S. at a large scale since 1966 [1]. This data has consistently shown that single-vehicle rollover crashes area a significant threat to the safety of heavy truck occupants. The use of a combination of crash data, biomechanical metrics, structural analysis, and highway parameters to develop a comprehensive strategy to minimize vehicle accident death and injury has been the backbone of safety improvements for many decades [2]. Further, coordinated efforts that include all relevant stakeholders such as government, industry, and research communities are generally provide the most beneficial and efficient outcomes. This has been a clear desire of the heavy truck industry for many years as exemplified by the recommendations provided to the National Vehicle Safety Advisory Council by the Motor Truck Manufacturers Division [3]. Coordinated efforts among stakeholders provides an opportunity for the benefit and evaluation of safety standards in conjunction with determining feasibility and the cost-benefit outcome of any proposed rules.

A three-phase cooperative research program managed by the Society of Automotive Engineers (SAE) in the 1990s followed this general framework to develop a set of recommended practices for evaluating truck crashworthiness. Cab-to-ground impact forces ranging from 150 kN to 250 kN and energy absorbed (cab only) of approximately 100,000 Nm were calculated with similar values reported for baseline and reinforced models [4]. A primary goal of the recommended practice for evaluating cab strength was to use two testing phases to reproduce both the lateral and vertical loading scenarios that were observed in 180 deg rollovers as these were lacking in the ECE Regulation 29 and a Swedish standard at the time. The ECE R29 test calls for quasi-static vertical load to be applied to the roof of the cab via a large platen with a peak force requirement of 98 kN. The Swedish standard required a maximum 147 kN vertical load followed by pendulum impacts to the A-pillar and rear cab wall. Both of these standards require a level of survival space to be maintained after loading. In the SAE recommended procedure the two test phases consisted of a dynamic impact (via sled or pendulum) to a cab rolled at 20° followed by a quasi-static roof test similar to the ECE R29 protocol. The energy value selected for the dynamic impact was not based on the amount of energy absorbed by the cab during the rollover reconstructions, but instead based on minimum roll energy tests which had no foundation in relation to occupant injury. The final energy value used in the recommended practice (J2422) was 17,626 Nm. The authors notes deficiencies in the ability to calculate the energy absorbed during a rollover event were noted as problematic to determining an appropriate test energy.

Subsequent to the large SAE-CRP the International Organization of Motor Vehicle Manufacturers (OICA) put together a working group consisting of heavy truck manufacturers with the goal of harmonizing truck cab standards. In the latest large scale effort related to heavy truck crashworthiness the NHTSA concluded that further work should investigate the potential effectiveness of reducing injury and death and the cost-effectiveness of countermeasures related to increasing the integrity and robustness of cab structures with respect to rollover [5].

This paper describes a framework for developing and/or updating test procedures that can improve the rollover crashworthiness of heavy truck cabs. Many advancements in crash data collection, reconstruction, finite element analysis, manufacturing processes, material specifications and costs, and injury metrics have been made since the development of current heavy truck cab test procedures. These advancements can be leveraged to support improvements in cab design that are feasible and cost-effective.

METHODS

Crashes of heavy trucks that produced serious or fatal injuries were identified with the FRC internal crash database. This database includes fully reconstructed heavy truck crashes with detailed medical records and vehicle information. For each crash the detailed LSYDNA finite element models of the vehicle and terrain, which had been produced previously, were used to simulate the rollover event. The deformation and internal energy of the cab as well as contact forces with the ground were calculated during each run. The orientation of the cab relative to the ground at the time of maximum initial deformation was determined for each case. The time of maximum initial deformation was defined as the first event with the greatest single increase in cab deformation, thus separating the primary roof intrusion event from subsequent loadings. Often a cab will experience the greatest magnitude of roof intrusion when and if it comes to rest on its roof, yet this does not necessarily describe the most injurious event.

A baseline cab structure, modeled in LS-DYNA and validated against the results of a SAE J2422 test, was subjected to select test conditions representative of the impact energy and orientation determined from the reconstructions. The test setup consisted of a flat faced platen on a sled constrained to move in a direction perpendicular to the platen face. The platen impacted a cab that was rigidly constrained at its mounting locations. The total mass of the sled was 5645 kg. The orientation between the cab and plate was defined using the following sequence of rotations and an example of the setup is shown in Figure 1. The cab was initially placed in an upright position with its x-z plane parallel to the face of the platen. The cab was then rotated about its roll axis a predetermined amount. Finally, the cab was rotated about the global z-axis which produced both a yaw and pitch relative to the platen face. Table 1 summarizes the test protocol. The baseline cab was subjected to each of the combinations listed in Table at a 35 kJ impact energy. The modified cab was subjected to the 60 deg roll, 30 deg yaw scenario at both 35 kJ and 80 kJ as this was determined to be the scenario that produced the greatest amount of damage in the baseline cab.

An additional drop test was conducted on the baseline cab fitted to a full tractor to investigate the effect of an unconstrained test on cab response. The cab was oriented relative to the ground at the same 60 deg roll, 30 deg yaw position as utilized in the sled impact scenarios.

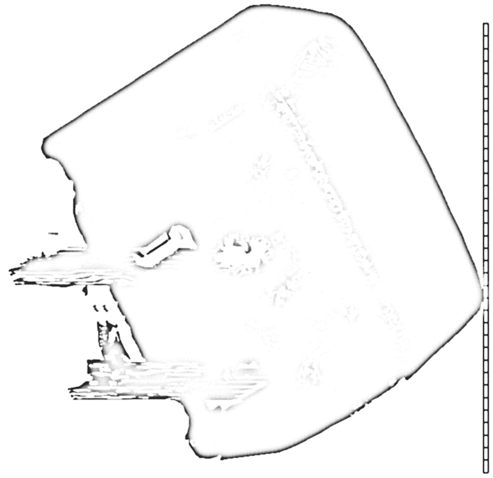

Figure 1 Baseline cab setup for 60 deg roll, 30 deg yaw platen impact (proprietary cab purposely distorted)

Table 1 Summary of simulated test protocol

	Yaw				
Roll	**0**	**10**	**20**	**30**	**40**
20	B35	B35	B35	B35	B35
40	B35	B35	B35	B35	B35
60	B35	B35	B35	B35/M35/M80	B35

B35 – Baseline cab, 35 kJ impact energy
M35 – Modified cab, 35 kJ impact energy
M80 – Modified cab, 80 kJ impact energy

The baseline FE cab was modified using manufacturing methods and materials available in the 1990s to improve crashworthiness, increase survival space, and reduce the risk of occupant injury in the reconstructed scenario. The modified cab was then evaluated against select test conditions to assess for comparison.

RESULTS

Due to the low counts of crashes investigated and the preliminary nature of this study some of the results have been normalized. It is not the intent of this work to propose any specific test procedure or energy level, but to demonstrate a methodology using data that was immediately available to the authors.

Three fully reconstructed heavy truck rollover crashes were identified for this preliminary analysis and are summarized in Table 1. The orientation at maximum initial roof deformation had a much greater range in the roll and pitch directions than in the yaw direction. Resultant roof deformation ranged from 408 mm to 793 mm. The amount of roof deformation was reduced from 793 mm to 255 mm with the use of a modified cab. The amount of energy absorbed by the cab varied from 32 to 50 kJ.

Table 2 Summary of reconstructed rollover crash response

Crash ID	**Orientation of cab at maximum initial roof crush (deg)**			**Maximum resultant roof crush (mm)**	**Energy absorbed by cab (kJ)**
	Roll	**Pitch (+ve nose up)**	**Yaw**		
1	131	27.8	50.8	408	43
2	180	6	40	553	50
3	116	-12	46	793	32
MOD3	112	-12	45	255	38

The vast majority of crash energy in typical heavy truck rollover crashes is dissipated through friction as the truck slides across the ground surface and only a relatively small percentage is associated with the damage related to the most harmful event (e.g. cab roof damage) [6]. This is demonstrated in Figure 2 which illustrates the total amount of energy that was dissipated through deformation (i.e. internal and eroded energy) vs the total amount of kinetic energy dissipated throughout the entire event. The total amount of energy associated with damage to the tractor, cab, and trailer was roughly 12 % of the total available energy.

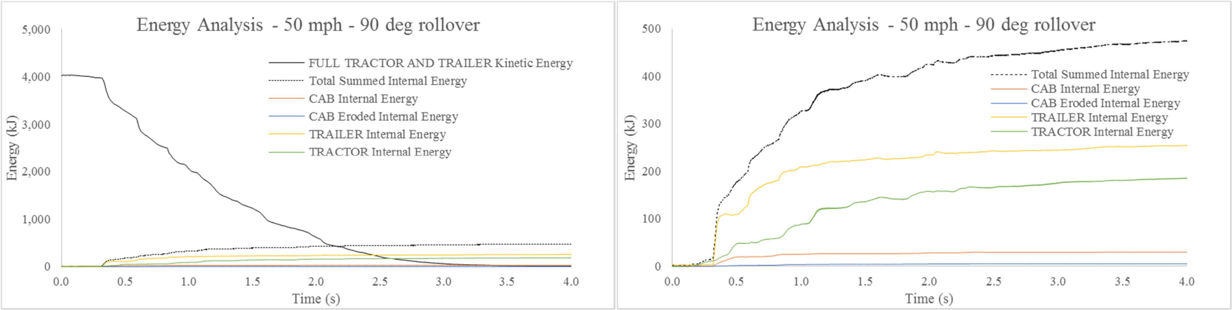

Figure 2 Energy summary for typical 90 deg heavy truck rollover

Platen motion was used to measure maximum cab deformation in the simulated sled tests. Cab deformation was highly dependent on the orientation of the platen relative to the cab as shown in Figure 3. Greater roll angles produced greater deformation. The maximum amount of deformation was achieved at a roll angle of 60 deg combined with a yaw angle of 30 deg. The lowest levels of deformation were 56% of the maximum value.

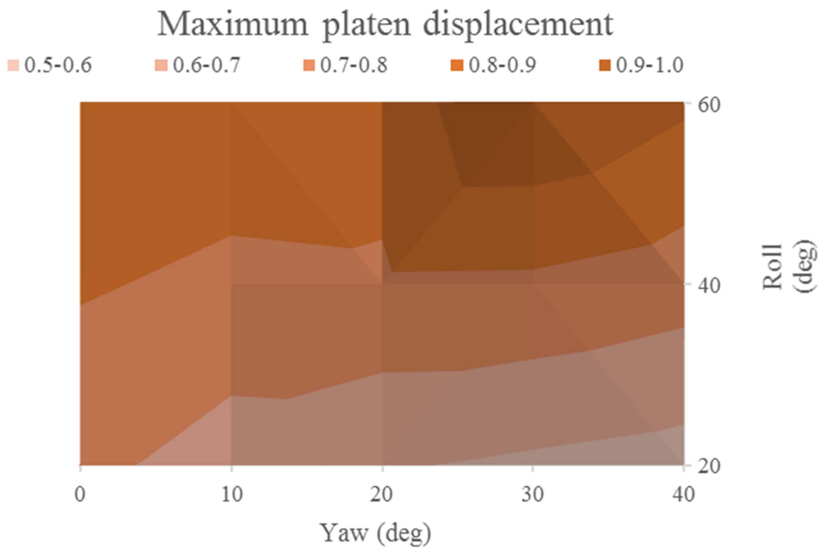

Figure 3 Contour plot of cab deformation vs orientation (data normalized to maximum value)

Platen force was inversely related to the cab deformation as described in Figure 4. The greatest platen force was measured in a 60 deg roll, 40 deg yaw orientation. Though, high force levels were also measured at 20 deg roll angles. It is expected that greater force values would be associated with lower deformations.

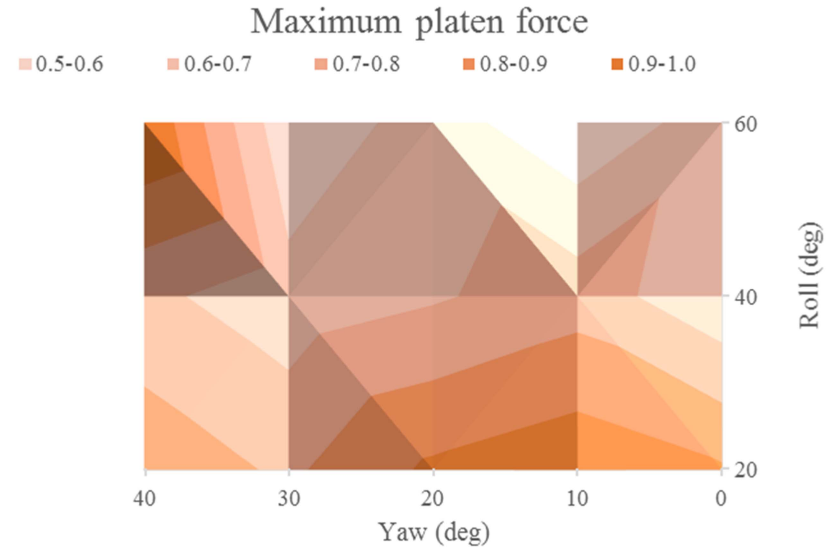

Figure 4 Contour plot of platen force vs orientation (data normalized to maximum value)

The internal energy absorbed by the cab was distributed in a similar pattern as the maximum cab deformation values. Figure 5 shows that the maximum energy was absorbed in the 60 deg roll, 30 deg yaw orientation but that the range in absorbed energy was relatively small. For all orientations the difference in the minimum and maximum internal energy was 10.9 %

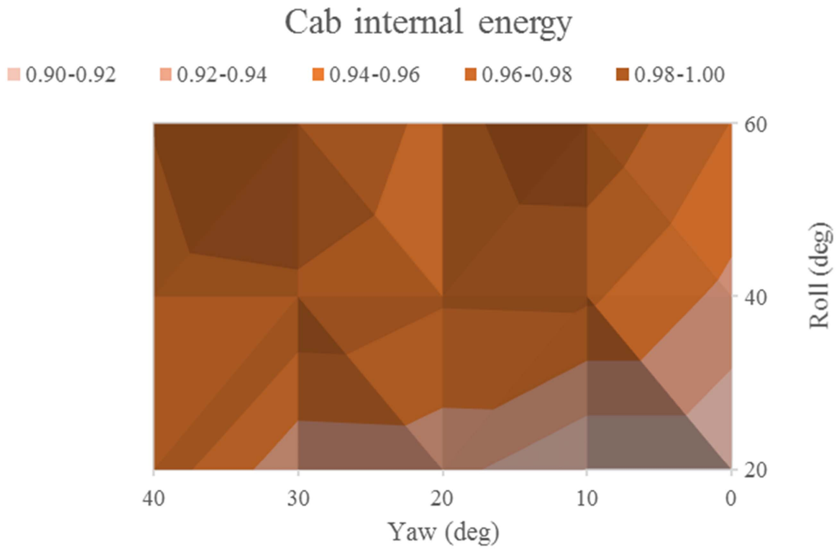

Figure 5 Contour plot of cab internal energy vs orientation (data normalized to maximum value)

The response of the modified cab to the 60 deg roll, 30 deg yaw sled impact demonstrated much less deformation yet similar amounts of internal energy. The cab experienced 60% less deformation and absorbed 4% greater energy. Under the 80 kJ sled impact (also at 60 deg roll, 30 deg yaw) the modified cab suffered 30% less deformation than the baseline did under the 35 kJ condition.

The drop test produced a maximum deformation equal to 81% of that produced in the sled scenario. The cab in the drop test absorbed 87% of the total energy absorbed in the sled test. After the initial impact with the ground in the drop test, which used a FE model of the full tractor and cab, the vehicle pitched rearward until the vehicle was horizontal. The tractor also rolled slightly toward the driver’s (left) side.

DISCUSSION

The results of this effort highlight the technical and procedural issues related to developing and improving crash test protocols for heavy trucks. It has also demonstrated, on a small scale, the ability to use reconstructed crash data to develop evidence-based test protocols that could be used to evaluate heavy truck cab crashworthiness in rollovers. Perhaps most importantly, this effort also demonstrated the ability to create a generic cab that could pass a given test. Notably no pass/fail test metrics were provided in this work, yet this is would be an additional step in the process.

The proposed framework includes the creation of a database of reconstructed heavy truck rollovers that produced serious and fatal injuries under reasonable circumstances and in which the cab would have the potential to mitigate those injuries. Existing crash databases would support this effort by providing nationally representative crash data to inform the project on exposure and risk. A range of impact conditions and response metrics would be produced through these reconstructions. A matrix of potential test conditions could then be developed using some threshold (average or 90th percentile) of these values. At this point it will be important to define those injuries and/or crash scenarios that the test protocol will aim to mitigate. This can be supported by parametric finite element analysis.

It will be important that all phases of the effort are coupled with an analysis of injuries and the biomechanical response of occupants. The relationship between the structural response of the cab and the risk of injury to an occupant is the most important feature of a crash test, especially its pass/fail criteria. Finite element modeling ATDs and human body models can be used to evaluate this relationship with respect to testing methods.

Generic cabs and tractors would be created in a virtual environment to parametrically study the effects of select test conditions. The use of a generic cab has advantages. It often invites a greater level of cooperation from industry partners as they are less inclined to be involved in a project that could potentially demonstrate less-than-ideal responses from their vehicles. It can also provide a platform on which to evaluate novel techniques that would otherwise conflict with existing designs. The results above demonstrated the sensitivity of cab deformation and energy absorption to orientation of an impacting platen. Additionally, the effects of various constraint methods for both the cab and the impacting device would have to be investigated to find the right balance between test repeatability and relevance to the real world.

Two primary paths for a new test standard are envisioned. The first, traditional, path would use a limited number of physical tests to evaluate the response of a cab under a very narrow set of conditions. The second path would use a combination of physical and numerical testing to evaluate the response of a cab under a wide range of conditions. The pros and cons of each path will be investigated to determine the potential increase in performance, cost, and desired outcome from a test plan. The advantages of coupling numerical with physical testing includes the ability to conduct full-scale rollovers under a wide variety of conditions in an efficient and cost-effective manner. Numerical testing also assists manufacturers to demonstrate due diligence. Such methods of allowing for some level of certification by analysis are already in use for aircraft seats and roadside hardware.

One key aspect of the test protocol development process will be to demonstrate the feasibility of producing a cab that can pass the test. The modified cab described above is an example of this. This cab was developed using materials and manufacturing processes that were available and in use by passenger vehicle manufacturers in the 1990s. It was demonstrated to successfully mitigate injuries in a reconstructed rollover test as well as improve the response in an example platen impact. By coupling the research of developing a test protocol with the demonstration of practical conceptual designs the chance of success of producing a more stringent test protocol, and therefore better cabs in the future, is improved. A logical next step would involve working with an industry partner to develop and test a physical concept cab that is capable of passing the required test.

Along with demonstrating the feasibility of passing the test method, it will be important to provide estimates of the cost-effectiveness of modified designs as well as appropriate lead times for potential changes in standards. This will require working closely with industry to develop designs that are within the capabilities of existing manufacturing technology. Again the use of injury and crash data will support the cost-benefit analysis and continue to provide an evidence base for all decisions.

CONCLUSIONS

It is clear that much of this framework is not entirely novel or new to crashworthiness test development, however it does apply the recent advancements in finite element analysis to test design which were demonstrated above. The current state of heavy truck cab crashworthiness calls for a review and update of existing recommended practices and crash tests standards. The improvements and advancements in data recording, finite element analysis crash data collection, reconstruction, manufacturing processes, material specifications and costs, and injury metrics should be leveraged at this time to develop a modern rollover crashworthiness test that help heavy truck cabs reach their ultimate safety potential. This research supports the recent efforts of the NHTSA and SAE in improving heavy truck cab rollover crashworthiness. It presents a framework for developing improved testing methods that should include state-of-the-art modeling techniques that are becoming increasingly relevant in the design and evaluation of vehicle safety. This work is directly relevant to the improvement of physical and virtual test methods and identification of enhanced performance measures in support of vehicle safety.

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