Development of a Simplified Finite Element Approach for Investigation of Heavy Truck Occupant Protection in Frontal Impacts and Rollover Scenarios

C. Silvestri Dobrovolny, N. Schulz
Email: c-silvestri@tti.tamu.edu
Texas A&M Transportation Institute
Texas A&M University System, 3135 TAMU
College Station, Texas, 77843-3135

Abstract

A finite element model combining a heavy truck conventional-type cabin structure, its interior components, ATD, and passive restraint systems was developed to simulate real-world typical crash scenarios, such as frontal impacts and rollover crashes. These crash scenarios are considered conditions for which there is need and still room for improvement in terms of occupant safety. This paper describes the modeling effort to develop a cabin structure with its interior components through reverse engineering and the development of simplified approaches to replicate finite element computer simulations of frontal impact and rollover scenarios.
The model was used to replicate head-on crashes into a rigid barrier at 35 mph which are representative of impact conditions typical of NHTSA NCAP tests. For this crash scenario, an existing FE full tractor-semitrailer model was employed to collect the typical crash pulse resulting from a head-on impact crash. The crash pulse was subsequently applied to defined locations of the new FE cabin model with inclusion of interior components, ATD, and restraint systems. Parametric simulations were then performed by varying characteristics of passive restraint systems and acceleration data from ATD body regions was collected to assist with the calculation of body injury levels for each simulated case.
The developed model was also employed to replicate a critical rollover event, determined to be the result of an evasive maneuver followed by an overcorrecting maneuver, with an initial truck speed of 60 mph. To replicate this sequence of maneuvers, a simplified approach was proposed by analyzing truck kinematics through the TruckSim software program. Subsequently, kinematics outputs were applied to the center of the floor of the LS-DYNA® finite element cabin model.
The researchers suggest future work to be conducted to address approach limitations, such as validating cabin interiors material models and including cabin deformation, which is not currently incorporated in the simplified proposed approach.

Background

According to the Census of Fatal Occupational Injuries for 2013 from the Bureau of Labor Statistics, the transportation and warehousing sector, which includes truck driving, has the second highest rate of fatal occupational injuries annually, second only to agriculture and forestry. Truck driving also accounts for the second most fatal occupational injuries annually, only after construction. The fatality rate per worker is over four times the national average, and a large majority of fatalities to transportation workers occurs in traffic crashes (Bureau of Labor Statistics 2015).

Interior crash protection has not yet received adequate attention for heavy trucks, as it did for automobiles. Among light vehicles, there have been numerous safety technologies implemented to make driving safer and decrease the carnage on the highways. In addition to safety belts and air bags (required for all passenger cars since the 1999 model year), the new car assessment program (NCAP) that was established in 1973, created market pressures for manufacturers to design safer cars. Crash testing and the NCAP star rating program have resulted in safer cars.

However, there has been significantly less development to protect truck drivers in crashes. Safety belt use is required by federal law under section 392.16 of the Federal Motor Carrier Safety Regulations. Usage rates of safety belts by commercial truck drivers have been increasing in recent years and currently are approaching those of light vehicle drivers. In 2007, about 65% of truck drivers were reported to be using safety belts in an observational study. By 2013, the rate had increased to 84% overall, with the highest rate reported for "box van" trucks, which includes tractor-semitrailers (FMCSA, 2014). However, there is no NCAP for heavy trucks or requirement for air bags.

The University of Michigan Transportation Research Institute (UMTRI) and the Texas A&M Transportation Institute (TTI) conducted a joint project to identify and characterize opportunities to protect heavy-truck drivers and occupants through improved passive restraints and more protective cab interiors, in the context of current Advanced Crash Avoidance Technologies (ACATs) (Silvestri Dobrovolny et al., 2015). Crash types not addressed by current ACATs were identified and characterized to support finite element analysis (FEA) of heavy truck occupant kinematics in these crashes. It was found that rollover accounts for about 50% of heavy-truck fatalities and frontal collisions account for about 35%. Rollovers and frontal collisions together account for about 85% of all heavy-truck driver fatalities. The authors also identified the most promising current ACATs - electronic stability control, forward crash warning and automatic braking, and lane departure warning - and developed estimates of how they would affect the crash population. It was estimated that if these three ACATs were fully deployed, they would reduce rollovers by about 40%, frontal collisions by about 21%, and truck driver fatalities by almost a third (Silvestri Dobrovolny et al., 2015). Though full ACAT deployment was estimated to result in about a 15% reduction in driver fatalities and incapacitating injuries in crashes in which the Most Harmful Event (MHE) is a collision with another vehicle, a significant number would remain and most would still be frontal impacts.

The project employed numerical simulations to analyze heavy truck occupant kinematics in the most severe crash types for truck drivers. The work developed within this project consisted of finite element computer modeling and simulation to direct investigations on occupant safety. FEA was used to analyze heavy truck occupant safety in terms of injury patterns and severity. Understanding injury types and injury sources for heavy truck occupants in relation to different crash scenarios will help identify opportunities to reduce injury severity through design of a more crashworthy occupant compartment and implementation of appropriate passive restraint systems.

The truck type examined here was a tractor-semitrailer. This is a common truck configuration, colloquially called an "eighteen wheeler," and is the workhorse truck of freight hauling in the U.S. Tractor-semitrailers were selected as the truck type to study because they are the primary truck configuration, because they account for most truck driver injuries and fatalities (Woodrooffe and Blower 2013), and because most of the studies on ACATs for trucks focus on the tractor-semitrailer combination.

The researchers used a currently available FE dummy model for their computer simulations and analyzed the kinematics of the occupant during replicated crash scenarios. Employment of the dummy model in the simulation of different crash scenarios allows collection of acceleration data from impact of different parts of the dummy with the interior components of the occupant compartment. The results can be used to calculate injury levels for the occupant in different crash scenarios. Understanding injury types for heavy truck occupants in relation to different crash scenarios will help with development of mitigation strategies to reduce injury severity through design of the occupant compartment and appropriate passive restraint systems.

One of the main focuses of this project was to develop a computer model and appropriate methodologies for use with finite element computer simulations to investigate the effectiveness of restraint systems in heavy trucks in a frontal impact and rollover crash scenarios. The FEA discussed herein were performed using the LS-DYNA explicit finite element code (Hallquist, 2015).

Modeling

Next, a brief overview of the process undertaken to create the front interior of the heavy truck is presented, as well as explanation on the choice for the dummy employed in simulations, and the methodology to develop a computer simulation of a rollover crash. LS-PrePost software was used to make many of the modifications and restore parts used in the heavy truck model.

Cabin Model Development

Recently, the Roadside Safety and Physical Security Division at TTI was involved in a project supported by the Department of State (DoS) to scan the outline of a cab-over-engine (COE) heavy truck. The scanning of the truck supported the development of finite element computer models of the truck components. Although this proposed study is considering employment of a heavy truck conventional cab, the provided COE DoS cabin model was morphed to fit the conventional cab style by flattening it out and making adequate adjustments in order to fit the proper geometry. The main adjustments made are listed below:

- Dimension from Front of Cabin to Back of Cabin:
  Old DoS Cabin = 81.1 inches (2060.12 mm)
  Morphed Cabin = 81.1 inches (2059.22 mm)
- Dimension from Left Cabin to Right Cabin:
  Old DoS Cabin = 94.4 inches (2396.27 mm)
  Morphed Cabin = 94.4 inches (2396.27 mm)
- Dimensions from Top of Cabin to Bottom of Cabin:
  Old DoS Cabin = 74.3 inches (1887.49 mm)
  Morphed Cabin = 92.1 inches (2339.02 mm)

The biggest adjustment made was with respect to the vertical dimension from the cabin top to the cabin bottom. Figure 1 shows different perspectives of the original COE DoS cabin model and the morphed conventional model.

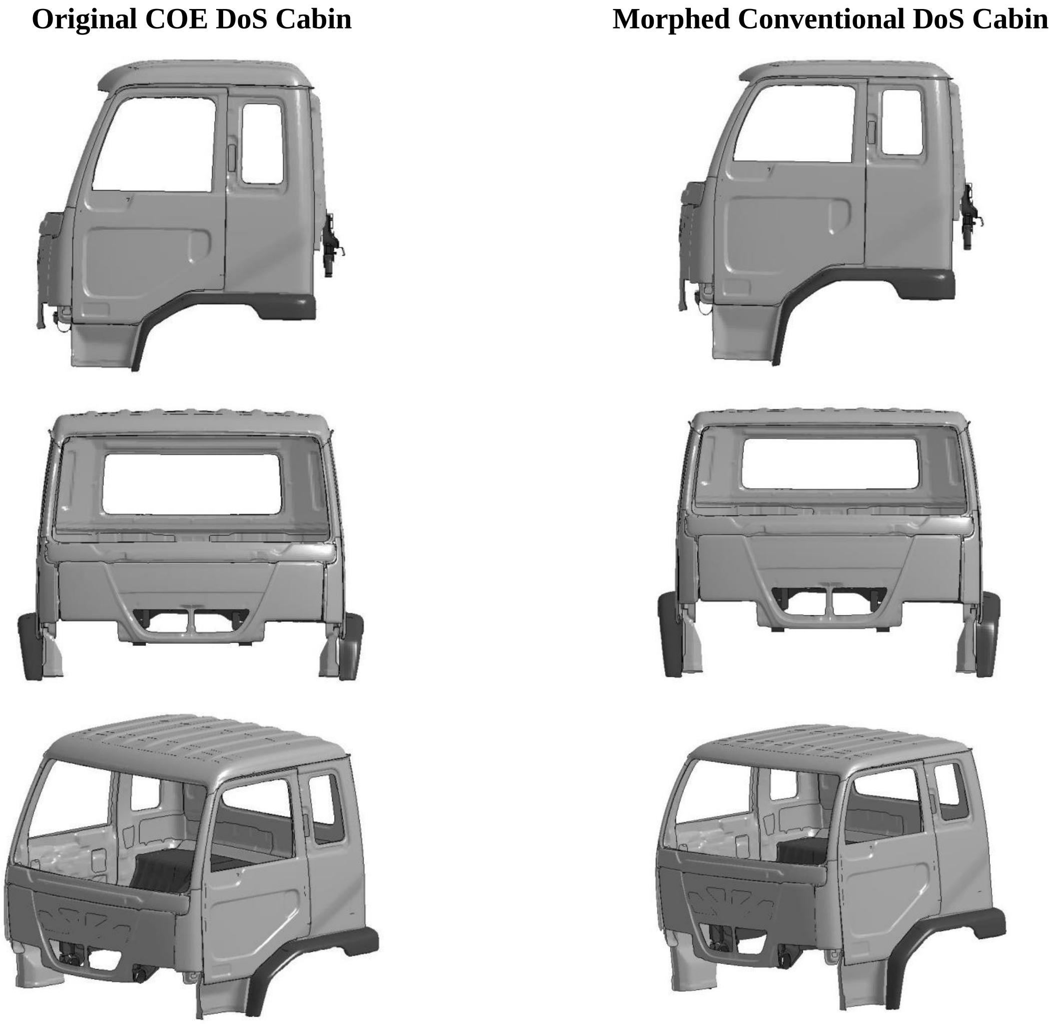
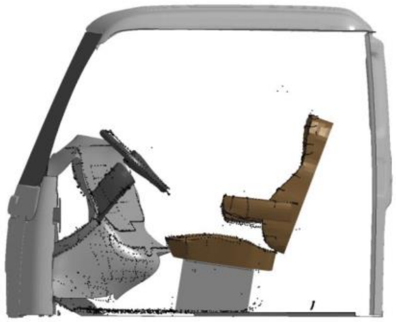


Figure 1. Original COE DoS cabin versus morphed conventional cabin models.

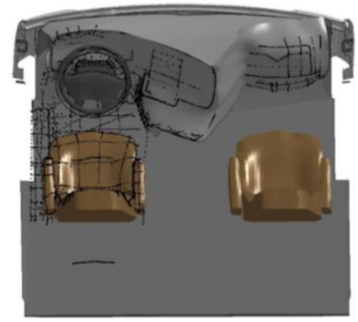
Currently no publicly available FE tractor-trailer models exist which include occupant compartment components. In order to model these components, cloud point scans of a Peterbilt 387 truck model were used to define the geometry of several key interior components which were later meshed and included in the full FE truck cabin model.

Cloud points were used as a basis for the 3-D development of the frontal interior of the truck. UMTRI used scanners and probes over the interior pieces of an actual truck to create an outlined image of cloud points on the computer. These dotted images were then used to create the finite element model employed in the computer simulations.

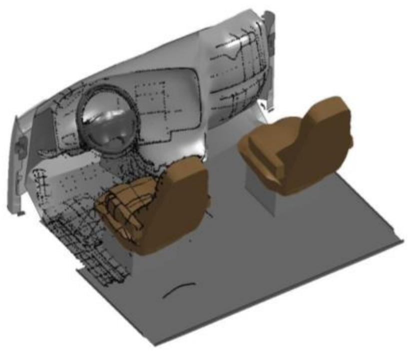
A mesh grid was applied over the image using LS-PrePost software to create a 3-D computer model. This methodology was employed to complete the surfaces for all other modeled cabin parts. The cloud points were used as a reference to apply surfaces to the different parts of the interior. The modeled interior surface parts were combined with the morphed truck cabin shell to complete the interior model (Figure 2).



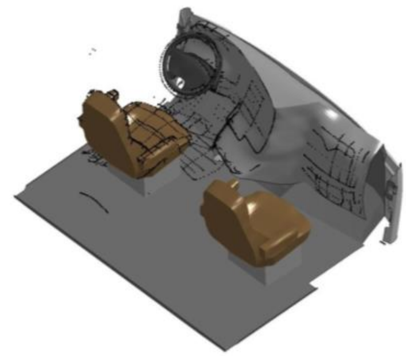
(a) Side View



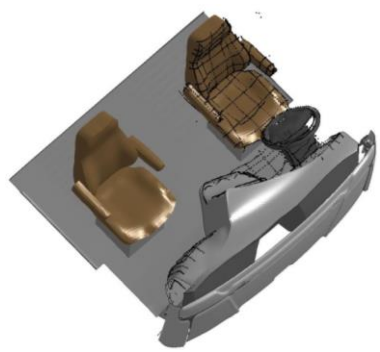
(b) Top View



(c) Left View



(d) Right View



(e) Frontal View

Figure 2. Perspectives of cloud points with surfaces in cabin.

Crash Test Dummy Finite Element Model

A finite element model of the Hybrid III 50th percentile male anthropomorphic test device (ATD) (also called dummy) was selected for employment in the study's computer modeling and simulations. The dummy model used in this project's simulations was provided by the Livermore Software Technology Corporation (LSTC). This finite element dummy model includes models of accelerometers located at critical body locations (head, chest, pelvis, left and right femur, and left and right tibia). The Hybrid III dummy provides an adequate model to evaluate injury criteria for collisions. Figure 3 shows different views of the finite element dummy model along with accelerometer locations.

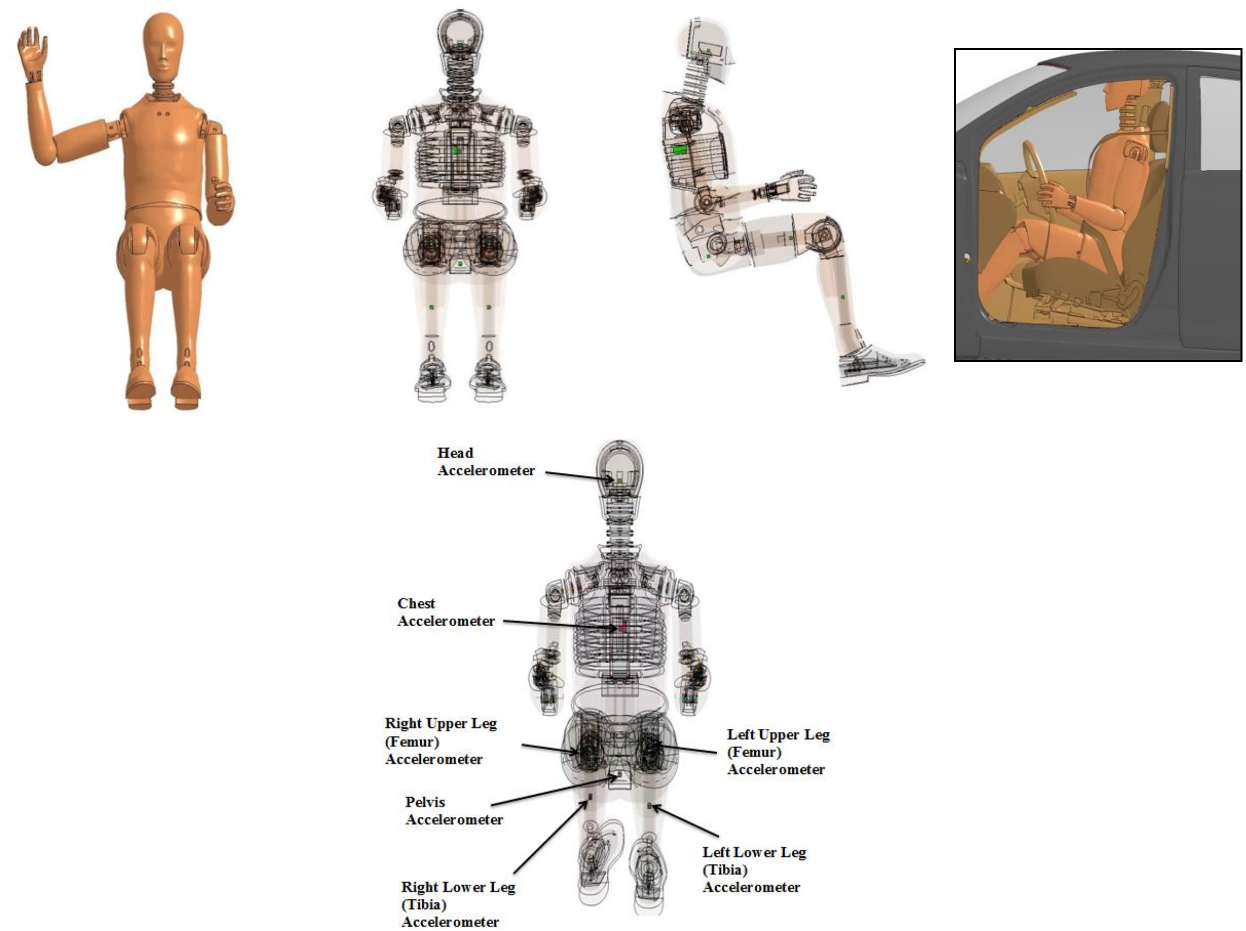


Figure 3. FE model of the Hybrid III 50th percentile male dummy.

Finite Element Seatbelt Model

An LS-DYNA finite element model of a three-point belt system was developed and modeled as a load-limiting seatbelt. The belt system consists of general 1D seatbelt elements and 2D shell elements. Also, several specialized elements were used to model specific parts of the seatbelt such as the pretensioner, retractor, and D-ring.

A load-limiting belt system is modeled through the use of a retractor system. Retractors operate in two different ways and allow belt material to be paid out or reeled in. The first way in which a retractor operates is in the unlocked role, which is when belt material is paid out, or reeled in under constant tension. The second way a retractor operates is the locked role, where a user-defined force-pullout curve applies. A seatbelt sensor element fires and acts on a retractor causing it to enter into a locked state and allowing the force-pullout relationship to take over. Typically, seatbelt sensors fire after a specified time after the simulation has begun. This approach for seatbelt sensors was similarly used for this study. The retractor will follow the loading curve in tension and will follow the unloading curve when no tension is in the belt. When the belt is in tension the retractor will give out belt material by lengthening the last element attached to the retractor. The last element will lengthen based on the force-pullout relationship of the retractor. A pretensioner was used in conjunction with the retractor and controls seatbelt elements to remove initial slack. Similar to the retractor, the pretensioner fires based on a timed seatbelt sensor. Shortly after the retractor engages and locks the pretensioner fires and engages and pulls in belt material to create 1.8 kN of tension in the belt. Once the tension in the belt reaches 1.8 kN the pretensioner disengages and the retractor takes over again.

There are two D-ring elements used in the three-point belt system. One is used for the lap belt and the other is used for the shoulder belt. D-rings allow the seatbelt to be re-directed with the option of adding some friction to the moving seatbelt.

The location of the D-ring and anchor positions is very important when modeling a seatbelt. Exact positions were provided by UMTRI as part of the cloud point scans for the D-ring and anchors. After the D-ring and anchor points were set for the FE seatbelt model an LS-PrePost seatbelt fitting tool was used to fit the seatbelt around the dummy chest and pelvis.
UMTRI researchers provided a working FE model of a seatbelt and the material, retractor, and pretensioner curves were implemented in the seatbelt model used in this study.

Airbag System Model

The National Crash Analysis Center (NCAC) developed a working FE model of a steering wheel and airbag that is publicly available for download on their website. This airbag model was used in the simulation to analyze the effects of an airbag restraint system on occupant injury criteria. The steering wheel used in the heavy truck cabin has a different geometrical shape relative to the FE steering wheel containing the airbag and developed by NCAC. Therefore the airbag was placed within the truck cabin steering wheel developed for this project.

According to previous research conducted on airbags, an input curve used to inflate the airbag was developed. Thirty milliseconds after impact the airbag begins to inflate, and it takes approximately 25 milliseconds to achieve full inflation. The airbag inflation input curve from the NCAC model was modified according to those two parameters.

Crash Scenarios Simulation Methodology

Frontal Simulation Setup

The step-by-step methodology performed to develop a successful FE frontal crash simulation is described next. A simplified methodology was developed to develop computer simulations of frontal crash scenarios (Figure 4).

First, a full scale crash impact was simulated employing an existing FE model of a tractor-trailer impacting a rigid barrier. The FEM combined tractor-trailer model consists of 391,390 nodes, 345,537 elements and 563 parts. The researchers developed frontal impacts with an initial speed of 35 mph to follow the Federal Motor Vehicle Safety Standard (FMVSS) 208 and NCAP testing standards which set test impact velocity for passenger vehicle between 30 and 35 mph.

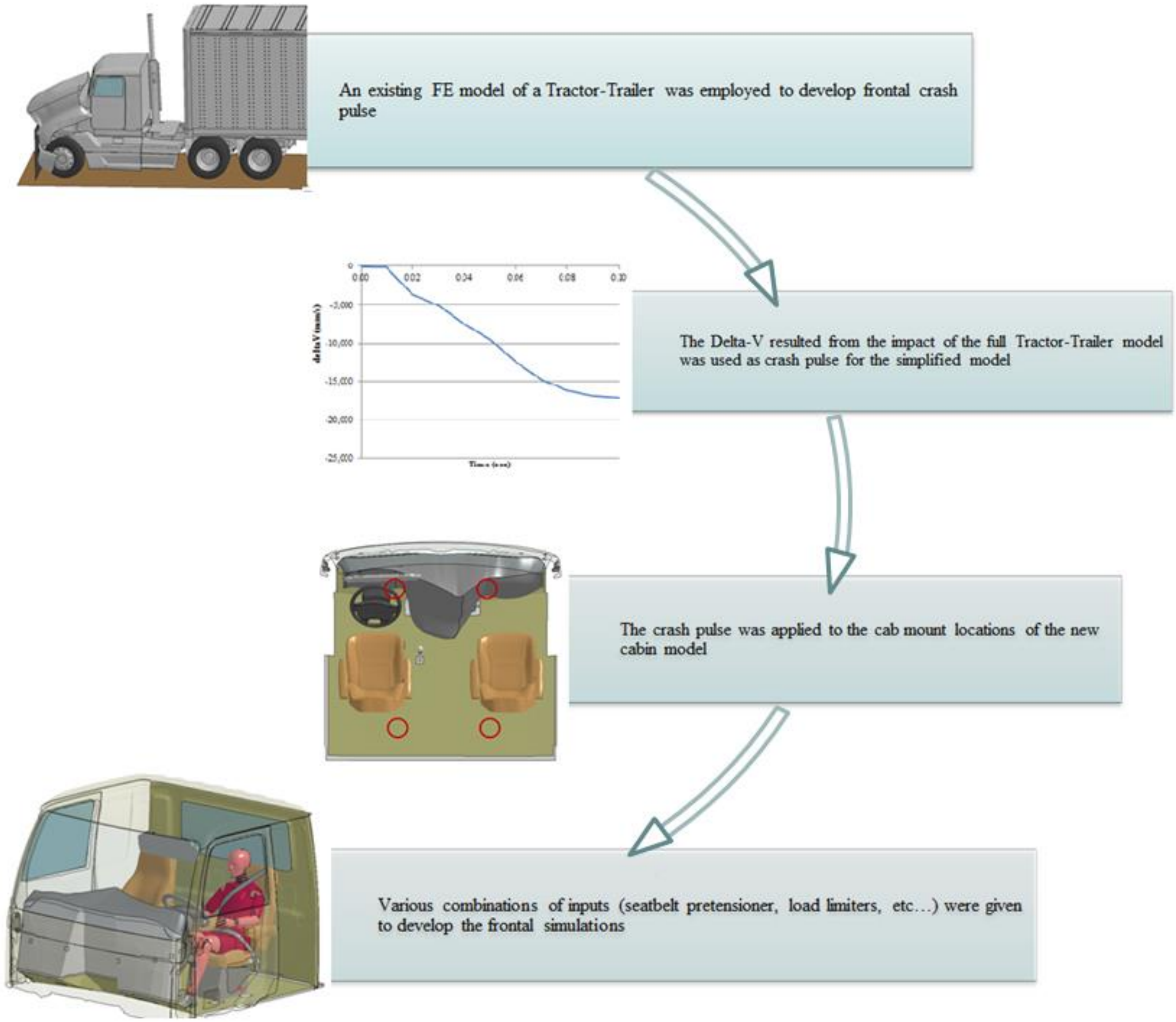


Figure 4. Frontal crash events FE simplified methodology.

Next, the crash pulse generated during this impact simulation was applied to the truck cabin model that was developed. The x, y, and z velocities were output at four different locations representing the four cab mount connections. A node was picked at these four locations to easily output velocity versus time from the simulation. The velocity curves were applied as a crash pulse to the newly developed truck cabin model at those same nodes locations.

A simplified approach was used by applying the velocity curve only in the x-direction at each of the four nodes, considering that the velocity in the y and z direction for these locations resulted being insignificant.

Once the derived crash pulse was appropriately applied to the developed cabin for use within the simplified methodology, an array of frontal impacts was replicated. Modifications of the conducted FE simulations consisted in varying seatbelt characteristics and use of airbag. Five different seatbelt conditions that were replicated:

- Baseline simulation incorporated basic seatbelt model with a pretensioner and no load limiter;
- Simulation with no seatbelt pretensioner;
- 4 kN load limiters;
- 8 kN load limiters; and
- D-Ring location was lowered

Each one of the above conditions was then replicated with inclusion of airbag. To assess the potential threat to occupants, the injury criteria of the Hybrid III 50th percentile male dummy was analyzed and a parametric evaluation was performed.

Rollover Simulation Setup

Rollover crashes for heavy trucks can cause significant injury to occupants and have become an increasing area of concern for roadside safety researchers. The purpose of this rollover study is to analyze vehicle kinematics during a rollover crash and to analyze occupant kinematics and safety.

TruckSim Rollover Event

One of the first steps conducted for this rollover study was selecting the type of rollover event. There are several different ways in which heavy trucks can rollover in a crash, so it is necessary to determine what type of event is most critical. Based off of a previous real-world crash data study conducted by Indiana Mills and Manufacturing Inc. (IMMI), it was determined that one of the most critical rollover events is where the vehicle performs an evasive maneuver to the left followed by an overcorrecting maneuver to the right (Chinni et al., 2007).

In order to develop a FE computer model of a truck cabin that can perform a rollover crash, it is necessary to know the kinematics of the cabin throughout the rollover. TruckSim is a dynamic vehicle modeling software for heavy trucks that was used to replicate the rollover event and analyze the kinematics of the truck. The truck model used was a tractor-trailer vehicle with a 3-axle tractor and a 2-axle trailer. The rollover crash in TruckSim was conducted by inputting a path for the tractor-trailer to follow. The rollover path was determined from an IMMI study (Figure 5) (Chinni et al., 2007).

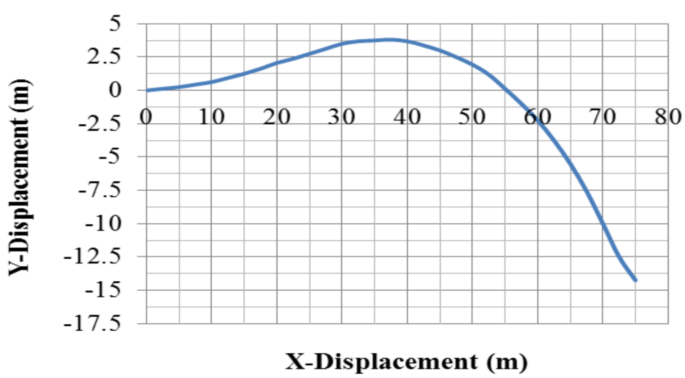
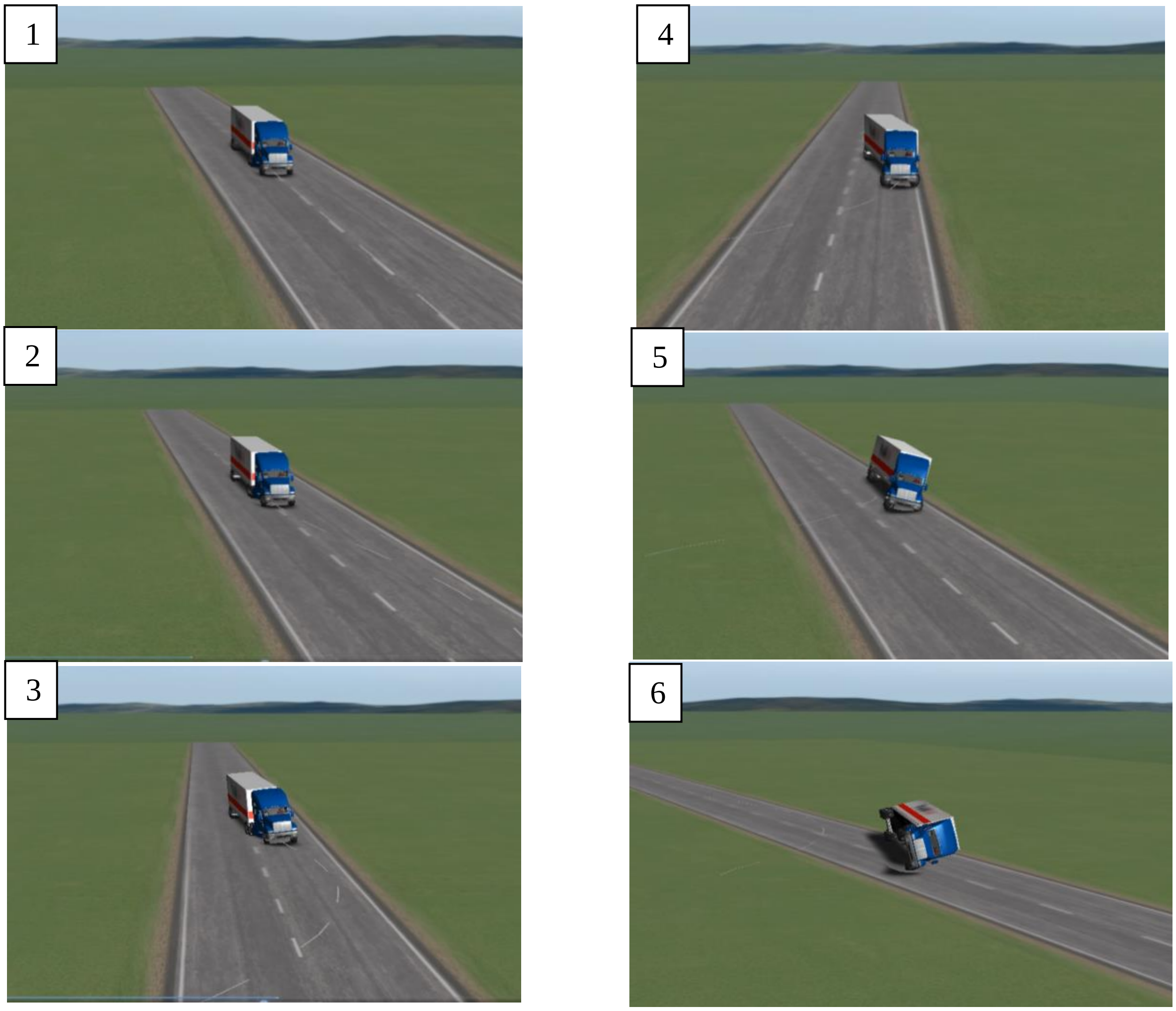


Figure 5. Rollover path as input into TruckSim tractor-trailer rollover event.

The tractor-trailer performed the rollover maneuver at 60 mph. Table 1 shows sequential frames of the TruckSim rollover event.

Table 1. Sequential frames of TruckSim rollover event.



Outputs of interest from the TruckSim rollover simulation were displacements at four cab mount locations. Measurements were taken in a FE model of a tractor-trailer for the exact locations of the cab mounts to determine where to output displacements from TruckSim. At these four locations x, y and z displacements were output over time. These displacement curves were then applied in our truck cabin model by BOUNDARY_PRESCRIBED_MOTION cards at the four locations.

Application of Rollover Maneuver to Truck Cabin

Taking the displacements at the four cab mount locations from TruckSim and applying them to our truck cabin model proved to be a difficult process. Several different approaches were tried to apply the displacements but many of them did not successfully capture accurate rollover kinematics. A brief summary is provided explaining the general approaches and the resulting final approach.

Initially the approach was to apply x, y and z displacements at four nodes at the location of the cab mounts via BOUNDARY_PRESCRIBED_MOTION cards. Several variations of this approach were tried but none of them proved successful. Investigation of the LS-DYNA manual

BOUNDARY_PRESCRIBED_MOTION card showed that no more than one node should be prescribed or unexpected results may be obtained. Accordingly, it was determined that applying displacement and rotation at the center of the floor would prove to be a better approach.

TruckSim was used again to output x, y, and z displacement along with x, y and z rotation at the center of the floor. These displacement and rotation curves were applied at the center node of the floor but the truck cabin was not able to successfully complete the rollover maneuver.

Another approach was tried by applying x, y, and z velocity instead of the displacement curves. The resulting simulation successfully captured the rollover maneuver. Therefore, this method was used to re-create the rollover crash for the truck cabin model.

Further Development of Truck Cabin Model for Rollover Event

There is a significant difference between the time it takes for a frontal crash event to occur and a rollover event to occur. A typical complete frontal crash impact can occur in about 0.5 seconds, whereas a complete rollover crash event can occur in about 4 seconds. The TruckSim full rollover crash was completed in 3.4 seconds. For finite element simulations a simulation time of that length can take several days of run time to obtain results. This is a result of the large number of computations that have to be performed. For the purposes of this study it was not feasible to allow such lengthy and costly simulations. Therefore, several changes were made to the truck cabin to simplify the model which would significantly reduce simulation run time.

First, the entire cabin was completely rigidized by changing all the material cards to MAT_RIGID. Only the dummy was not rigidized in our complete model. A majority of finite element computation time is spent on material stiffness; therefore, changing the parts to "infinite" stiffness drastically cut down simulation time.

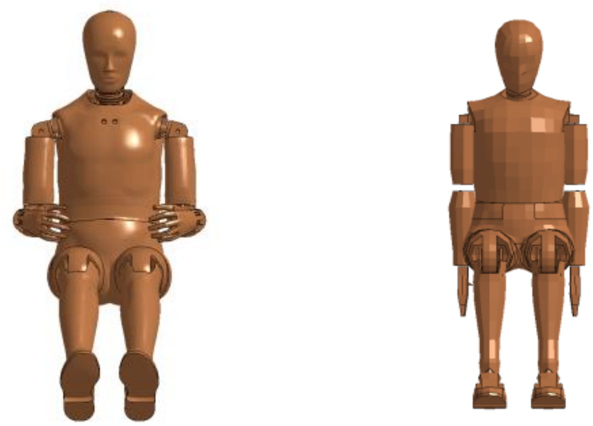
Second, all truck cabin parts were constrained to follow the floor by the CONSTRAINED_RIGID_BODIES card. Originally the parts were connected together by beam spotwelds or constrained nodal rigid bodies. These types of connections only work for parts that have non-rigid material properties. This approach no longer worked for the rigidized cabin resulting in the constrained rigid bodies approach. Essentially, this approach combines all the rigid truck cabin parts together and treats it as one big rigid part.

Finally, the contact definitions were reduced to one AUTOMATIC_SURFACE_TO_SURFACE contact between the dummy and the rest of the truck cabin. Contact algorithms are another aspect of finite element computer simulations that can cause long computation time. Therefore, removing extra contacts and developing one simple contact definition significantly reduced run time.

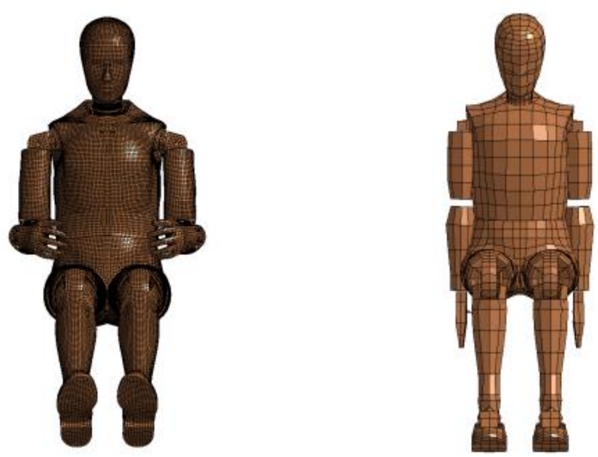
Inclusion of Hybrid III 50th percentile Male Dummy

After developing a successful truck cabin model that could perform a rollover maneuver, a detailed Hybrid III 50th percentile male dummy was positioned in the driver seat. An initial simulation was run with the positioned dummy and no seatbelt. The total simulation time was 3.4 seconds, which is the length required to complete the rollover maneuver. At about 0.8 seconds the simulation terminated due to numerical stability in the dummy. It was determined that a lower time step would be needed to allow the simulation to run the full length but this would result in very long and costly simulations. Due to time and budget constraints researchers proceeded to include a simplified version of the Hybrid III model referred to as the fast model.

Figure 6 compares the fast model to the detailed model. The fast Hybrid III model allowed a successful rollover simulation run and was used for all rollover simulations conducted. However, the fast Hybrid III model did not produce reliable injury criteria results and as a result only dummy kinematics were analyzed during the simulations.



(a) Without Mesh



(b) With Mesh

Figure 6. Comparison of detailed dummy model (left) and fast dummy model (right).

Summary and Conclusions

This research represented here is the product of a joint project to identify opportunities to reduce truck driver fatalities and injuries in traffic crashes in the context of the projected full deployment of ACATs.

This project was intended to represent a pilot study for the investigation of overall heavy trucks crashworthiness and areas of improvement for occupant safety. Researchers focused on identifying specific areas for future research aiming at improving occupant protection for truck drivers. Additionally, researchers developed a methodology that can be employed and /or adapted to conduct future research within heavy truck occupant safety with use of computational analysis. Researchers focused on overrepresented impact conditions from real world crash data, for which it is believed to be room for improvement in terms of occupant safety. In addition, researchers evaluated the effectiveness of passive safety restraints from FE computer simulations performed with and without use of these restraints.

An essential area of the FE simulations was the development of the truck cabin model. An integral part in developing the truck cabin model was the development of occupant compartment components. Furthermore, researchers developed FE models of seatbelt restraint systems which were included in the truck cabin model with the scope of investigating their effects on occupant dynamics and injury.

This project was conducted as a pilot study and there were important limitations encountered during the development of the computer simulations. Deformation of the truck cabin exterior was not considered during the rollover crash. Although this is not a realistic assumption, still it was considered to simplify modeling techniques and produce shorter simulations. Researchers suggest inclusion of cabin interior into tractor-trailer model to consider deformation of tractor-trailer vehicle.

Interior component material properties were not validated for the truck cabin model. Validated material properties for heavy truck interiors are not publicly available and due to budget constraints researchers were unable to conduct material coupon testing for the different interior parts.

The rollover simulation did not consider subsequent collision with the ground during the rollover event. Impact with the ground can cause significant injury to the occupant during the rollover crash. An FE fast Hybrid III 50th percentile male dummy provided by LSTC was used to represent the occupant during the rollover crash. This FE dummy model is a simplified version of the detailed dummy model. Complications arose with use of the detailed model for such a long simulation resulting in the use of the simplified model. The injury criteria results from the simplified model were not reliable and as a result researchers did not analyze injury criteria during the rollover crash. Researchers suggest future inclusion of the detailed model to analyze injury criteria for the different body regions of the dummy.

Researchers suggest future work be conducted to address the limitations of the project. This includes conducting interior material testing, consideration of deformation, and consideration of subsequent contact with the ground during a rollover crash, and inclusion of a detailed dummy model. Researchers suggest future work be conducted to analyze the effects of different types of seatbelt designs such as a four-point seatbelt and a five-point seat integrated belt to improve occupant safety during frontal and rollover crashes. Furthermore, researchers suggest analysis of side curtain air bag system to prevent occupant head contact with the left door during a rollover crash.

Acknowledgements

This research project was supported by the Center for Advancing Transportation Leadership and Safety (ATLAS Center). The ATLAS Center is supported by a grant from the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Transportation, University

Transportation Centers Program (DTRT13-G-UTC54). The ATLAS Center is a collaboration between the University of Michigan Transportation Research Institute (UMTRI) and the Texas A&M Transportation Institute (TTI). The authors acknowledge and appreciate the following for their guidance and assistance: David Eby (ATLAS Center Director, UMTRI) and Robert Wunderlich (ATLAS Center Associate Director, TTI) for support and funding of project through ATLAS Center; the Department of State (DoS) for funding scanning of truck cabin used in computer simulations; Dan Blower (Associate Research Scientist, UMTRI), Jonathan Rupp (Research Associate Professor, UMTRI) and Jingwen Hu (Associate Research Scientist, UMTRI) for collaborative assistance with this study; Akram Abu-Odeh (Research Scientist, TTI) for internal assistance with TruckSim and truck cabin modeling.

References

Bureau of Labor Statistics, "Current Population Survey, Census of Fatal Occupational Injuries, U.S. Bureau of Labor Statistics", U.S. Department of Labor, 2015.

Chinni, J., M. Miller, et al. (2007). Tractor-Trailer Rollover Crash Test.

FMCSA, "Commercial Motor Vehicle Safety Belt Facts. Washington, DC, 2014.

Hallquist, J.O., "LS-DYNA Keyword User's Manual, Volume 1", Livermore Software Technology Corporation, Livermore, California, 2015.

Silvestri Dobrovolny, C.; Schulz, N.D.; Blower, D. and Benedetti, M., "Identifying the Potential of Improved Heavy Truck Crashworthiness to Reduce Death and Injury for Truck Drivers", Report Number: ATLAS-2015-4, ATLAS Center Program, 2015.

Woodrooffe, J. and D. Blower D., "Heavy Truck Crashworthiness: Injury Mechanisms and Countermeasures to Improve Occupant Safety", Ann Arbor, MI, University of Michigan Transportation Research Institute: 112, 2013.