Evaluation of the Injury Risks of Truck Occupants Involved in a Crash as a Result of Errant Truck Platoons

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Abstract

Platooning is an extension of Cooperative Adaptive Cruise Control (CACC) that realizes automated lateral and longitudinal vehicle control while moving in tight formation with short following distances. The truck platoons are expected to include at least five trucks with drivers in the first and the last trucks. This paper discusses the methodology and presents results of a single tractor-van trailer impact into a concrete barrier, which is a dedicated approach for a broader truck platooning implication research funded and supported by Safety through Disruption (Safe-D) University Transportation Center (UTC).

First, full scale crash impacts were simulated with the LS-DYNA® software employing an existing tractor-van trailer FE model and a detailed model of a concrete bridge system. Impact criteria were those set in the Manual for Assessing Safety Hardware (MASH) standards, for a specific Test Level condition. The impact simulation of the tractor van-trailer against the concrete barrier was calibrated against the full scale crash test conducted by the Midwest Roadside Safety Facility (MwRSF) based on vehicle behavior. Calibration of the system was also assessed based on barrier damage after impact, which was achieved by utilizing erosion model of the barrier concrete, and plastic strains for the reinforcement components. Then, a previously developed truck cabin model, with inclusion of interior structures, was utilized to conduct simulations to assess occupant risks during the impact event. The motion of the truck cabin was then prescribed based on the displacement time histories of more than 8 nodes recorded in full crash truck-barrier simulations. The accuracy of simplified cabin motion relative to the full truck motion was verified against displacement time histories of a node set which include cabin nodes different than those used in prescribed motion. The injury risks of truck occupants involved in a crash as a result of errant truck platoons were evaluated using dummy and human occupant models representing a 50th percentile male. The occupant LS-DYNA models employed in this study were the HIII dummy and THOR dummy. The occupant models were setup in a seated driver posture and restrained using specific seatbelt restraint systems, which included a retractor, a pretensioner and D-rings. The kinematic and dynamic measures included in well-defined injury criteria corresponding to various human body regions (e.g. HIC, Nij) were recorded and the occupant risks of injury were assessed based on injury curves published in literature. Additional simulations with the models developed in this study could help to understand if any roadside safety device improvements and/or platooning constraint modifications will be necessary before implementing truck platooning.

Introduction

Platooning is an extension of Cooperative Adaptive Cruise Control (CACC) that realizes automated lateral and longitudinal vehicle control while moving in tight formation with short following distances. The truck platoons are expected to include at least five trucks with drivers in the first and the last trucks. It is unknown whether the capacity and adequacy of existing roadside safety hardware deployed at strategic locations is sufficient to resist a potential impact from a fleet of multiple trucks at high speed, which may occur as a result of errant truck platoons. It is also unknown how these impacting trucks might interact with roadside safety barriers after veering off the course of their platoon and what are the occupant risks associated with such impacts.

In this study, a methodology was developed to simulate a single tractor-van trailer impact into a concrete barrier. The same methodology will be applied to examine how the existing roadside safety devices will perform under multiple impacts at close proximity during a potential impact from a fleet of multiple trucks at high speed, which may occur as a result of errant truck platoons, and to evaluate the injury risks of truck occupants.

Methods

Development of the finite element models of the longitudinal barriers

Various categories of roadside safety devices including flexible, rigid, semi-rigid, redirective, non-redirective and breakaway devices were designed to serve a specific purpose. These safety devices were prioritized for evaluation based on application and identified potential risks to motorists. The Manual for Assessing Safety Hardware (MASH) incorporates tractor-van trailer tests in Test Level 5 (TL5) and Test Level 6 (TL6) impacts [2]. Flexible systems such as guardrails are not designed to have a significant reserved capacity after the first impact. Other systems, such as bridge rails, however, are usually conservatively designed for the anticipated impact loads. Considering the associated risks and likeliness of the impact scenarios, TL5 bridge rails and TL5 median longitudinal barriers were identified as the most appropriate roadside safety features for impact assessment. The Manitoba Constrained-Width, Tall Wall Barrier tested at Midwest Roadside Safety Facility (MwRSF) was selected as a representative bridge rail for this study [1].

The Manitoba bridge rail consists of a single slope barrier with a height of 1,250 mm (49-1/4 in.), base width of 450 mm (17-3/4 in.) and top width of 250 mm (9-7/8 in.). Concrete mix with 28-day compressive strength of 45 MPa (6,500 psi) and steel reinforcement consisting of Steel Grade 400W Canadian Metric Rebar was used for the test installation of the bridge rail and deck [1]. The test installation layout and details of the crash test setup are presented in Figures 1 and 2. The Manitoba barrier was designed as two segments – upstream and downstream, with a 168 mm gap between the segments, in order to simulate a joint in the bridge rail and deck. Steel end caps were cast into the ends of the bridge rail adjacent to the gap and a cover plate was placed over the joint and bolted to the upstream side of the barrier. The crash testing is performed with the tractor-van trailer impacting just upstream from the simulated joint in the bridge rail. To make sure that the interior section of the barrier could also withstand the impact during the crash test, traverse rebar spacing in the barrier end section were modified such that the end section had the same capacity as the interior section (i.e. 874 kN -196 kips) [1].

A layout of finite element (FE) model was developed in LS-DYNA to simulate this test (Figure 3). The barrier FE model consists of a single segment with total length of 45.72 m (150 ft.), as opposed to the full-scale crash Manitoba barrier testing of the end section in the test MAN-1. Constant stress solid brick elements (50 mm x 50 mm) were used to model concrete and 2x2 Gauss quadrature beam elements were used to model the rebar in the barrier assembly. MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_024) was selected as the material model for the rebar [3]. The Young's modulus of elasticity of 200,000 MPa (29,000 ksi), Poisson's ratio of 0.3 and yield strength of 400 MPa (58 ksi) was specified. The failure of rebar bars was modeled using element elimination with a 20% failure strain threshold. The reinforcing steel was constrained in concrete using CONSTRAINED_BEAM_IN_SOLID (CBIS) card [3]. The concrete elements were modeled using MAT_CSCM_CONCRETE (MAT_159) [3] with a compressive strength of 45 MPa (6,500 psi). The failure of the concrete model was modeled using a failure elimination approach defined by MAT_ADD_EROSION card [3]. After running multiple simulations with various parameters, 9.45% effective plastic strain criterion replicated the reasonable concrete erosion observed in MAN-1 crash test.

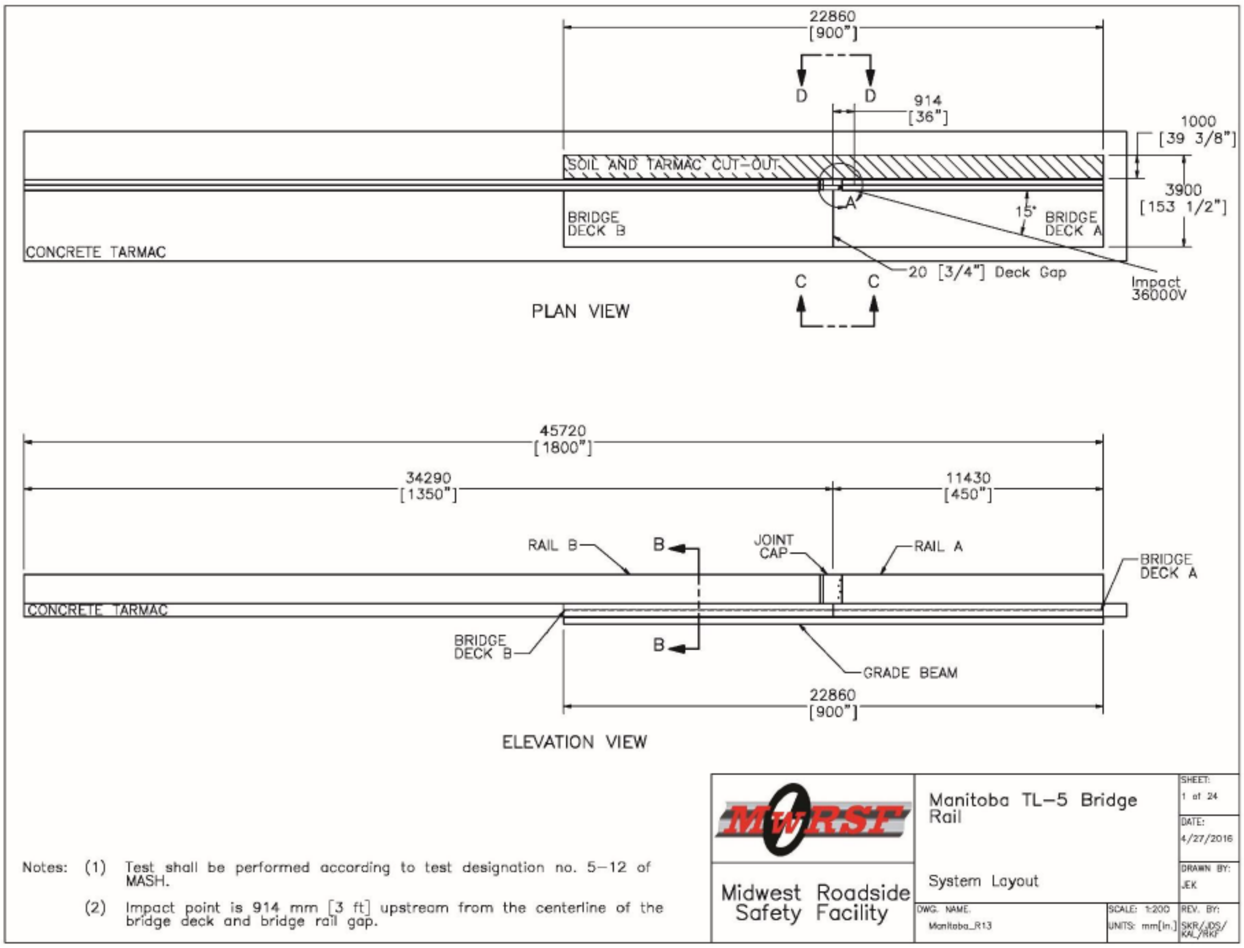


Figure 1: Test Installation Layout, Test No. MAN-1 [1]

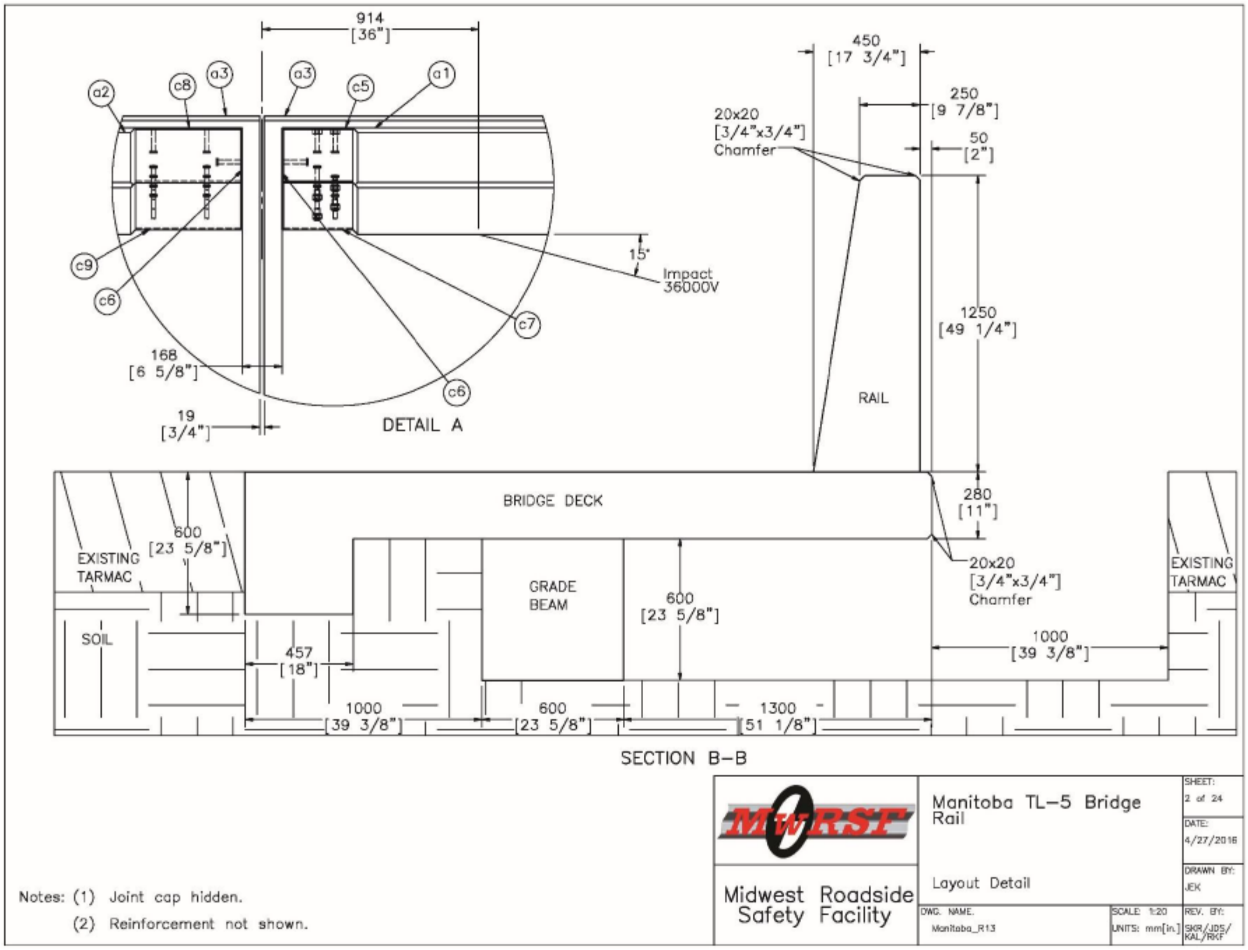


Figure 2: Test Layout Detail, Test No. MAN-1 [1]

Simulations of truck to barriers impacts

An existing proprietary tractor-van trailer FE model was used by the Texas Transportation Institute (TTI) to simulate the tractor-barrier impact. This model was initially developed by the National Crash Analysis Center (NCAC) and then it was publicly released by National Transportation Research Center, Inc. (NTRCI) [4-7]. Several modifications were made to the model by TTI including but not limited to geometry, mesh size, connections, material properties and suspension over a period of time in order to improve the truck behavior. The overall length of the trailer is 14.63 m (48 ft.) and the tractor length is 6.5 m (21.2 ft.). The tractor-van trailer model has 583 parts and 378,901 elements. The ballasted tractor-van trailer weighs 36,170 kg (79,741 lbs.).

The friction coefficients between the truck tires and the barrier, the truck body and the barrier and the truck tires and ground were set as 0.45, 0.2, and 0.85, respectively. The contacts between truck beams to concrete, truck body to concrete and truck body to reinforcement were modeled using CONTACT_ERODING_NODES_TO_SURFACE, CONTACT_ERODING_SURFACE_TO_SURFACE and CONTACT_AUTOMATIC_NODES_TO_SURFACE cards, respectively [3]. The stresses and displacements of the impacted barrier at the end of the simulation were stored using DYNAIN files [3]. The pre-impact configuration of the tractor-van trailer model is illustrated in Figure 4. Some calibration of impact simulation was performed to match the tractor-van trailer vs. barrier interaction observed in testing.

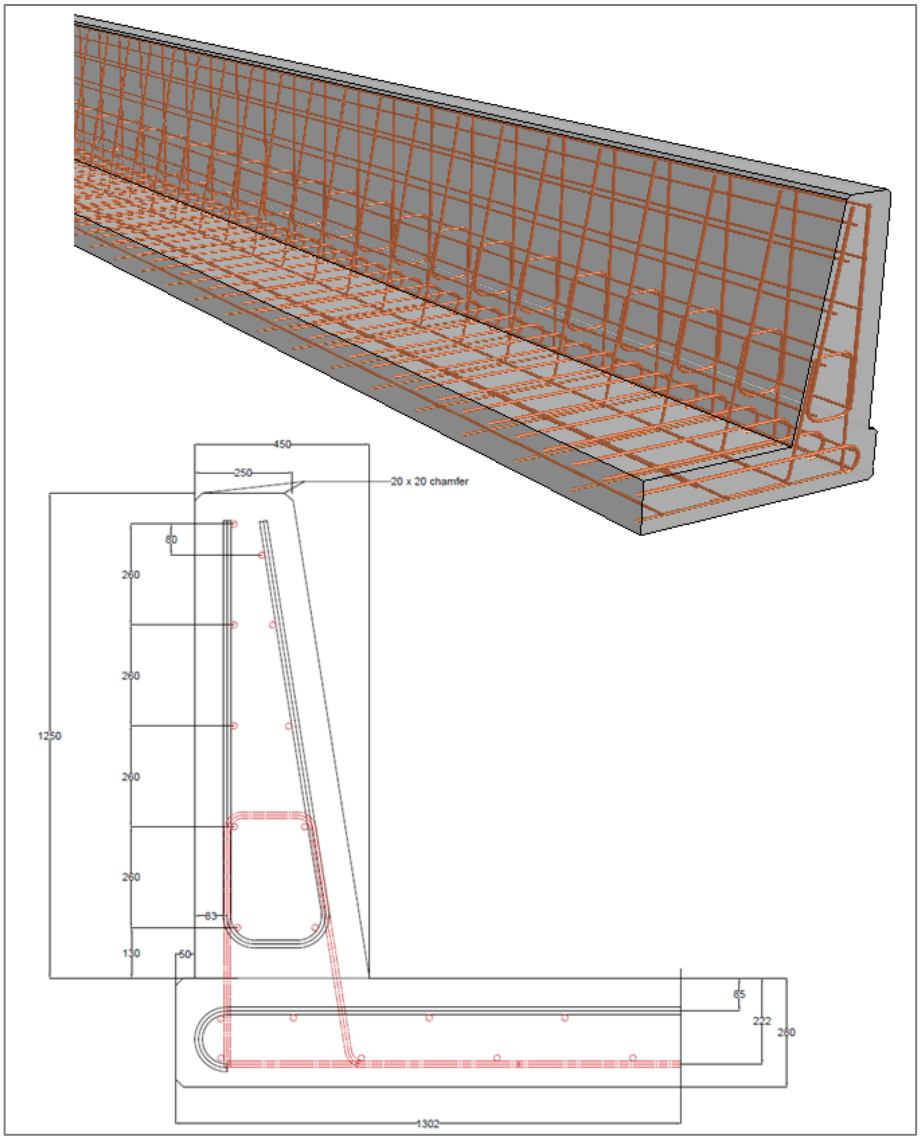
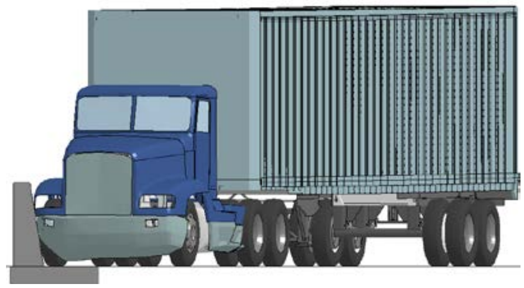


Figure 3: Cross-Section and Layout of Manitoba Barrier FE Model (dimensions in mm)



a)

b)

Figure 4: Front (a) and Top View (b) of Tractor-Van Trailer at the Beginning of Impact

An overall approach followed to complete the collaborative effort involved in the project is illustrated in Figure 5. While the barrier performance and vehicle stability with a full tractor-van trailer model was performed by TTI team, the occupant injury risks were assessed using a cabin-only model with interior parts and dummy models by VT team. A cabin-dummy-only model, driven by applying prescribed motion to the cabin nodes recorded in full tractor-barrier simulation, was preferred, as opposed to full tractor-van model with interior and dummy, to assess occupant risk. This approach was chosen not only because of proprietary issues but also because it would restrict the computational costs and avoid numerical instabilities associated with very large models.

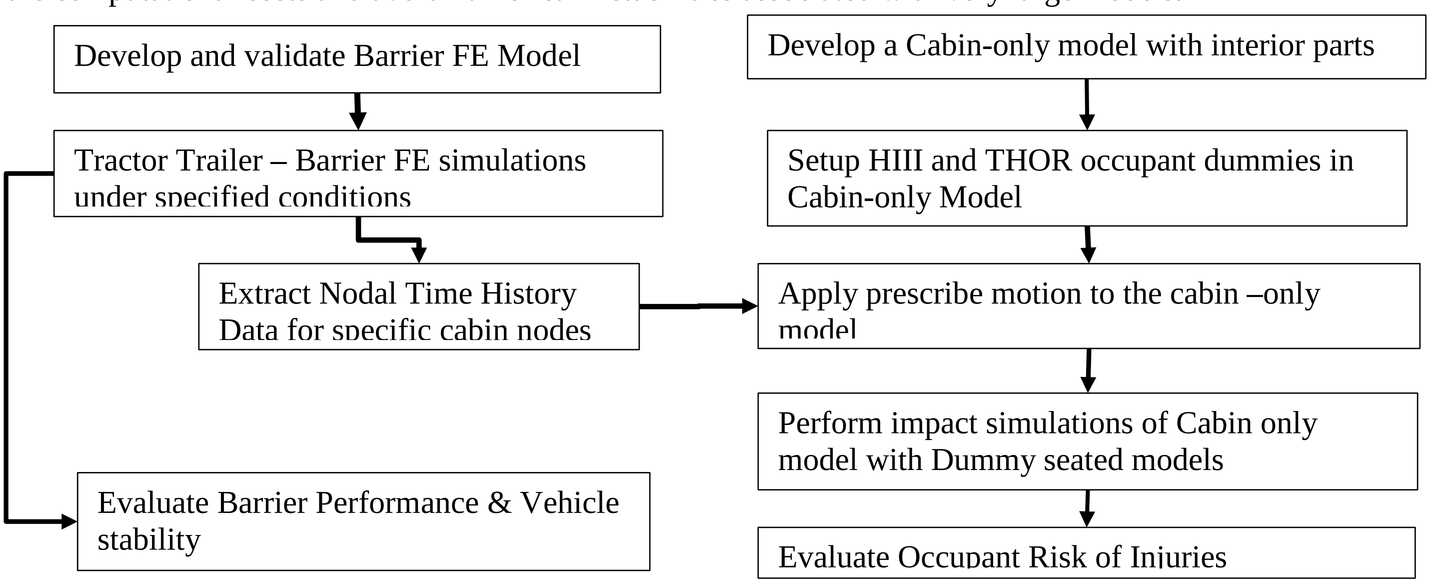


Figure 5. Overall Research Methodology

Simplified model of truck cabin and Finite element models of dummies

The cabin model of the tractor-van trailer was extracted and used to develop the cabin-only model. Since the original full tractor-van trailer does not include the interior cabin parts, the seats and the steering wheel column systems were added from another existing cabin-over-engine FE model. Other interior structures, such as the dashboard, were also added after they were successively scaled to match the cabin-only model. Material models of interior parts were assigned based on similar data from publicly available FE vehicle models or in-house material data. The motion of cabin-only model was prescribed based on the displacement time histories of 8 nodes recorded in the tractor-van trailer during barrier impact FE simulation. Four of these nodes are located on the cabin floor and the other four nodes are located on the cabin roof (Figure 6).

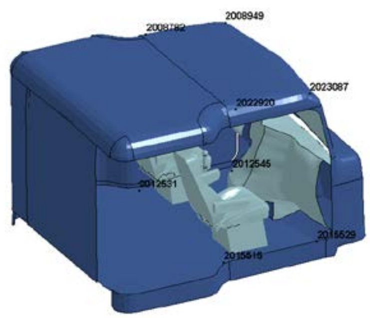


Figure 6. The locations of prescribed motion points in the cabin-only model

The accuracy of the cabin-only model in term of replicating the kinematics of the cabin of the whole tractor model was verified by comparing the displacement time histories of several nodes not included in prescribed motion.

The Hybrid-III and the THOR dummy models [8-10] were setup in the cabin-only model. Hybrid-III dummy is the most widely used dummy in vehicle crash tests to evaluate occupant protection. The FE model of the Hybrid-III dummy used in this study was provided by LSTC (Livermore, CA, USA)[11]. The model consists of 367 parts, 276,025 nodes and 451,769 elements, and was validated at component level against various calibration test data (e.g. Neck extension/flexion, Thorax impact). Similarly, the THOR (Test device for Human Occupant Restraint) dummy is an advanced impact 50th percentile adult Anthropomorphic Test Dummy. A FE model of the THOR developed by NHTSA and their collaborators [12] and updated according to recent modifications[9] was used in this study. The THOR FE model was calibrated and validated previously against component certification test data by CIB-VT computational group [8, 9, 13]. It contains 222,292 nodes and 444,324 elements, and allows simulations with a time step of 0.65 µs.

In this study, the occupant models were seated, and specific FE models of 3-point seatbelt systems were developed to restrain them on the seat. The same seatbelt system, which includes a retractor, a pretensioner and two D-rings was used for both dummy models (Figure 7). The positions of the dummies were adjusted to simulate a driver posture with hands holding the steering wheel, and feet placed on the ground [14].

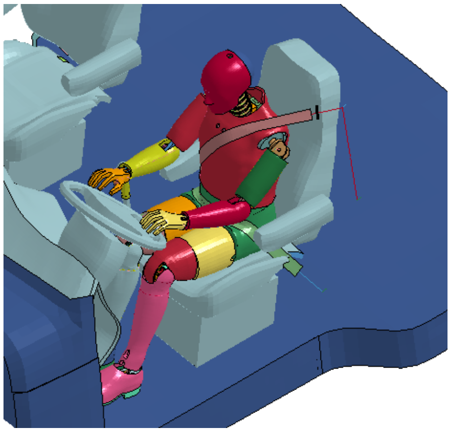
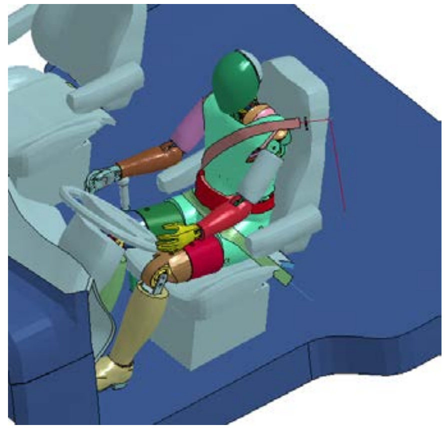
a)  b) 

Figure 7. Occupants models seated inside the simplified cabin model a) Hybrid-III dummy model b) THOR dummy model

Evaluation of injury risks of truck occupants involved in a crash

Injury measures obtained from the FE simulations of the Hybrid III/THOR dummy in the driver seat were used to determine the likelihood that an occupant would have sustained significant injury to various body regions [15, 16]. Well-accepted injury criteria were used in this study to quantify the driver risk of injuries during the tractor-to-barrier impact (Table 1).

Table 1 Injury Parameter Cutoff Values Associated with Possible Injury Protection Ratings

Body Region	Parameter	IARV
Head	HIC-15	700
Neck	N_{ij}	1.00
	Neck axial tension (kN)	3.3
	Neck compression (kN)	4.0
Chest	Thoracic spine acceleration (3 ms clip,g)	60
	Sternum deflection (mm)	-50
	Sternum deflection rate (m/s)	-8.2
	Viscous criterion (m/s)	1.0
Leg and foot	Femur axial force (kN)	-9.1
	Tibia-femur displacement (mm)	-15
	Tibia index (upper, lower)	1.00
	Tibia axial force (kN)	-8.0
	Foot acceleration (g)	150

The values of the injury assessment reference values (IARVs) represent the borders between acceptable and marginal ratings for a given injury parameter recorded during a crash test. Acceptable ratings correspond to measures somewhat below (better than) the IARVs, and good ratings correspond to measures well below the IARVs.

Abbreviated Injury Scale (AIS), created by the Association for the Advancement of Automotive Medicine, is defined to classify the probability of injury and describe the severity of individual injuries. It represents the threat to life associated with the injury rather than the comprehensive assessment of the severity of the injury [17, 18], and AIS3+ (serious level) curves were used for injury risk analysis.

While short descriptions of the injury criteria used in this study are briefly outlined below, the reader is referred to [19] for a more detailed treatment.

Injury Criteria – Head (HIC)

The head injury criterion (HIC) is determined on the basis of the head acceleration. In the Hybrid-III and the THOR dummy FE model, the HIC is achieved by nodal output of acceleration from the center of gravity of the head. Head acceleration recorded during impact event is employed to calculate HIC_{15} value as follows:

$$HIC = \max\left[\left[\frac{\int_{t_1}^{t_1} a(t)dt}{t_2 - t_1}\right]^{2.5} (t_2 - t_1)\right]$$

In addition, the probability of skull fracture (AIS≥3) is given by the formula

$$p(fracture) = N\left(\frac{\ln(HIC) - \mu}{\sigma}\right)$$

where μ and σ are the cumulative normal distribution parameters (μ=7.45231 and σ=0.73998).

Injury Criteria – Nij

Neck injury criteria are evaluated on the basis of normalized neck injury criteria. N_{ij} is defined as the sum of normalized values of loads and moments.

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}}$$

F_{int} and M_{int} are critical values: for the Hybrid-III model, F_{int}= 4,500 N and M_{int} = 155 Nm; for the THOR dummy model, F_{int} = 4113 N and M_{int} = 78 N. The probability of neck injury (AIS≥3) is given by the formula

$$p(AIS \geq 3) = \frac{1}{1 + e^{3.227 - 1.969 N_{ij}}}$$

Injury Criteria – Thoracic

Chest deflection relative to the sternum during impact event is employed to calculate chest injury probability. D_{max} is the maximum value of the dummy deflection (D). While the chest deflection is obtained by using a rotary potentiometer in the Hybrid-III dummy, the THOR chest deflection is achieved by measuring nodal distances for both the left chest and right chest. Due to these differences, there are different probabilities of chest injury (AIS≥3) for the Hybrid-III dummy

$$p(AIS \geq 3) = \frac{1}{1 + e^{3.7124 - 0.0475 D}}$$

And for the THOR dummy

$$p(AIS \geq 3) = 1 - exp(-[\frac{D}{e^{4.4853-0.0113age}}]^{5.03896})$$

Where the displacement *D* is in mm.

Injury Criteria – Femur

The maximum axial femur loads were recorded to calculate the risk of femur injury. The probability of femur injury (AIS≥3) for both the Hybrid-III and the THOR dummies is given by the formula

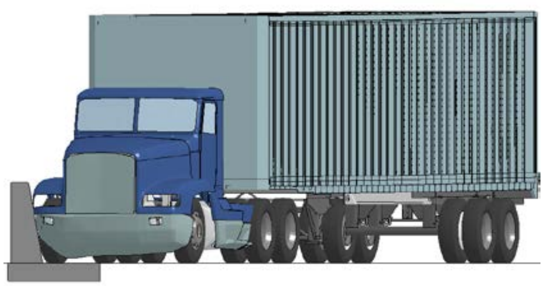
$$p(AIS \geq 3) = \frac{1}{1 + e^{4.9795-0.326F}}$$

where *F* is in kN.

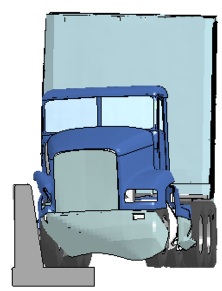
Results and Discussion

Barrier Performance

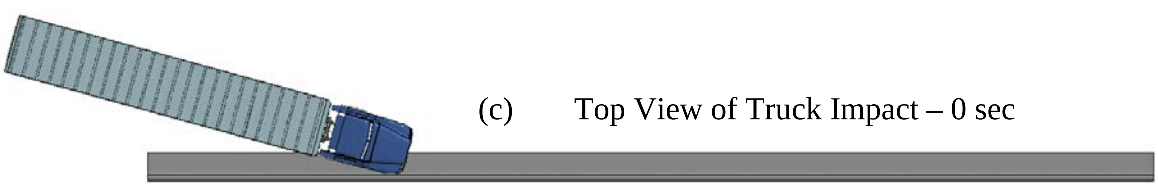
The barrier model was impacted by the tractor-van trailer model at an angle of 15.2 degrees and speed of 83.2 km/h (51.7 mph) about 10.52 m (34.5 ft.) from the upstream end of the barrier, corresponding to the MAN-1 test [1]. It was observed that the impacting vehicle was successfully contained and redirected by the barrier (Figure 8). Due to the impact, the barrier reached the maximum dynamic displacement of 50 mm (1.97 in.) about 0.72 seconds after the first contact which was comparable to the value of 52 mm (2 in.) recorded in the MAN-1 test [1]. The permanent nodal displacement of the barrier because of the impact was 44 mm (1.73 in).



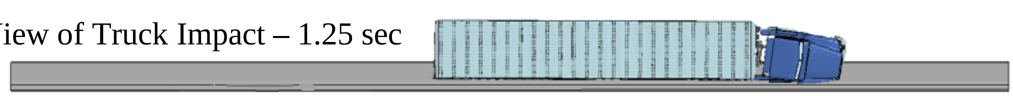
(a) Front View of Truck Impact – 0 sec



(b) Front View of Truck Impact – 1.25 sec



(c) Top View of Truck Impact – 0 sec



(d) Top View of Truck Impact – 1.25 sec

Figure 8: Initial (at 0 sec) and Final (at 1.25 sec) Configuration of the Manitoba Barrier

Energy Values

As the truck impacting against the barrier is a closed system, the total energy of the system is conserved. The total energy of the system at any point during the simulation is the sum of kinetic energy, internal energy, sliding interface energy and hourglass energy. At any time during the simulation, the total energy of the system should be equal to the kinetic energy of the vehicle at the beginning of the impact. As it can be observed (Figure 9), about 20% of the initial kinetic energy of the vehicle is dissipated in the form of sliding interface energy. Similarly, about 5% of the initial kinetic energy converts to internal energy. The hourglass energy of the system is less than 1%. Approximately, 70% of the total energy of the system is in the form of kinetic energy at the end of the simulation; this energy is due to the remaining velocity of the impacting truck.

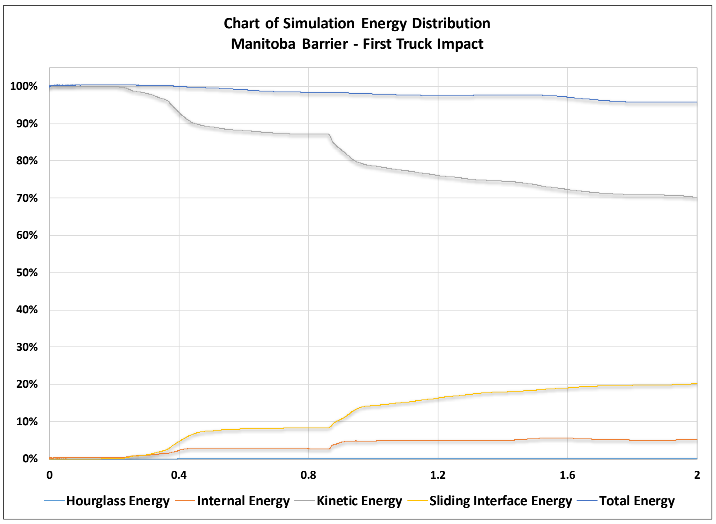


Figure 9: Energy Distribution Time History– First Truck Impact on Manitoba Barrier

Vehicle Stability

The frame comparison between the MAN-1 test and computer simulation during the impact event, starting at the time of first contact between the tractor-van trailer and the barrier (t=0ms), was illustrated in Figures 10 and 11. Both the physical truck and the FE truck model were stable during the impact events (no rollover).

Time (sec)	Test No. MAN-1	Computer Simulation
0		
0.5		
1		
1.25		

Figure 10: Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Front View (Rosenbaugh et al., 2016)

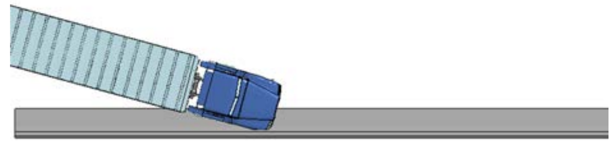
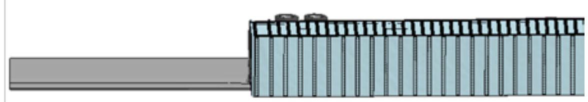
Time (sec)	Test No. MAN-1	Computer Simulation
0		
0.1		
0.38		
0.78		

Figure11. Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Top View [1]

Barrier Damage

The tops of both the physical barrier and the FE barrier model after impact are illustrated at the location of concrete spalling (Figure 12). Erosion occurred at the top of the barrier beginning at about 13.19 m (43.3 ft.) from the upstream end and extended about 0.75 m (2.5 ft.). Almost all of the 50 mm (2 in.) top layer of solid elements from the front side (impact side) to the back side of the barrier was eroded at the described location with a line of second-to-top layer of elements also eroded on the front side. In addition to erosion, cracks could potentially occur at the areas where the concrete strain values are the highest. The maximum plastic strain of about 5% was observed in traverse rebar in a very small region at the top of the barrier where the concrete erosion occurred. Most of the reinforcement had negligible or no plastic strain. Minimum damage occurred to the barrier during the crash test with contact marks, gouging, spalling and minor cracking. Concrete spalling with maximum depth of 52 mm (2 in) was observed beginning at the downstream end of the joint cap, i.e.11.85 m (38.9 ft.) from the upstream end of the barrier setup, and extended about 1 m (37 in.) downstream [1].

(a) (b)

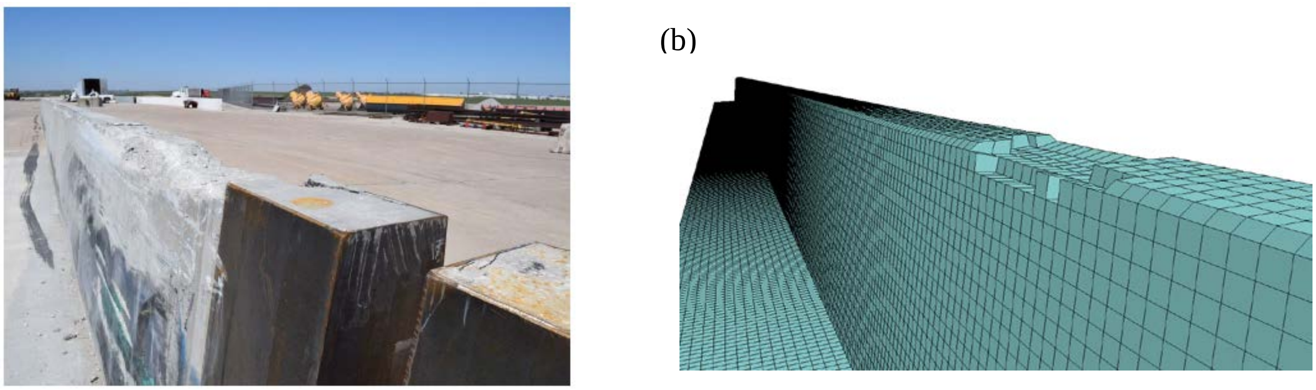


Figure 12: (a) MAN-1 Crash Test – Barrier Damage [1] vs (b) FE Simulation

The current result showed the design of Manibota barrier in this study was reliable enough to allow no rollover during the impact event and the stability of vehicle was guaranteed[20]. The damage to the barrier was relatively small, since the observed maximum plastic strain was only about 5%, which occurred in a very small region at the top of the barrier where the concrete erosion occurred. Most part of the reinforcement had negligible or no plastic strain. The design of Manibota barrier will also be tested in the future for more impact events from truck platooning.

FE simulation of simplified cabin model with dummy

The truck platooning impacts to the Manitoba barrier with deck case were simulated using the Hybrid-III and the THOR dummy models. To verify the difference between the full truck cabin motion and the cabin-only model, the displacement time histories of certain 4 nodes (randomly chosen and different than those used in prescribed motion) were recorded in full and simplified truck cabins and compared with the original full tractor FE model. The displacement differences were very low in x and y directions, and slightly higher in z direction. Overall, the maximum difference was less than 2 cm, which is small enough to suggest that the cabin-only model sufficiently approximate the motion of the full truck cabin, so it can be used in the occupant injury assessment. The motions of occupant models during the impact were illustrated (Figure 13). It can be observed that the seatbelt system effectively protected the occupant by restraining the occupants on the seat.

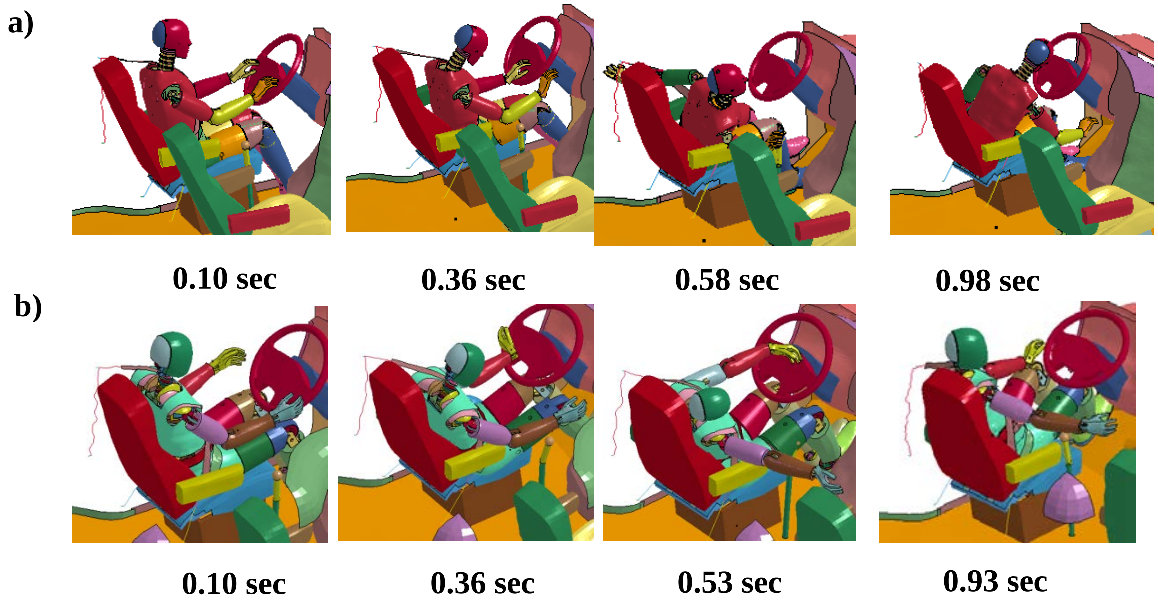


Figure 13. Motions of occupant models during impaction, a) Hybrid-III dummy model b) THOR dummy model

The values of maximum injury values recorded during the crash simulation showed to be much below the IARVs which suggests low injury risk for tractor drivers. Three injury values (HIC, chest deflection and femur axial forces) were less than 20% of IARVs (Table 2).
The highest HIC_{15} were observed during the first part of the tractor-to-barrier impact. The side /sliding impact scenario showed to be less aggressive than in a typical front crash scenario resulting in very low injury risk for drivers. The neck injury probabilities showed to be higher than other body parts. Comparing the results with the dummy motions (Figure 13), both dummy models had about 30 to 40 degree of inclination angle during/after the impact, which made the potential neck injury to be close to ten percent. The chest injury probability is the second highest one among all four sections of body in this study, though it is still relatively low (less than 4% for two dummies). The methods obtaining the chest deflection in the two dummies are different, but the results presented similar low injury risk. The femur injury risk is one of the lowest injury risks in this study. The result showed low risk (less than 1%) for both the Hybrid-III and the THOR model. The maximum absolute axial force occurred around 0.4 second, which is about 0.2 second after the cabin impacting with barrier.

Table 2. The injury risk of driver predicted by Hybrid III and THOR FE models

Injury criteria	**Hybrid-III** (value /injury probability AIS3+)	**THOR** (value /injury probability AIS3+)
Head – HIC_{15}	82.04 / 0.00%	124.90 / 0.02%
Neck - N_{ij}	0.52 / 9.51%	0.47 / 8.69%
Chest Deflection	11.09 [mm] / 3.97%	33.12 [mm] / 3.20%
Femur	925.74 [N] / 0.92	602.20 [N] / 0.83

Occupant Injury Measure

The overall injury risk assessment for the tractor drivers, called Occupant Injury Measure, was calculated by summarizing the individual AIS3+ Injury risk probabilities of each injury risk value (Table 3) [21]. The formulation (AIS3+) of Occupant Injury Measure (OIM) is derived from OIM proposed in the CAMPARS study. The predicted OIM values from both FE dummy models were higher than 85%, which corresponds to relatively low injury risks for occupants. In addition, the results from both dummies are similar, which also validate the setup in this study.

$$OIM_{AIS3+} = [1 - p(HIC15)][1 - p(N_{ij})][1 - p(Chest\ Deflection)][1 - p(Femur)]$$

Table 3. Occupant Injury Measure

OIM	Value (%)
Hybrid-III	86.10
THOR	87.64

The safety issue during truck platooning impacting with barriers had never been systematically evaluated before. Based on low OIM values derived in this study, the injury risk of a belted driver will be relatively low during first impact with a Manitoba barrier. In future, multiple impacts corresponding to the truck platooning accident scenario will be simulated. In addition to dummy models, the use of human models, such as Global Human Body Modelling (GHBMC) model [22-27] are planned to help better understand the possible injuries during these impacts.

Conclusions

A detailed reinforced barrier and deck model was developed and calibrated for an initial impact in order to be able to assess the performance under subsequent truck impacts as a result of errant truck platoons. The simplified cabin FE model with interior components has been developed and verified with full tractor motion data. The difference between the cabin-only model motion and the full tractor motion is negligible. A 3-point seatbelt restraint system was developed and mounted on the cabin-only FE model for both the Hybrid-III and the THOR dummy FE models to replicate the tractor-to-barrier impacts. The injury risks of vehicle drivers during the barrier impact were shown to be relatively low which suggested that regular seatbelt system can reasonably protect the occupants. The methodology presented in this study is currently applied to simulate the expected multiple impacts during truck platoon accidents.

References

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