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

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Abstract

Truck platooning comprises a number of trucks equipped with automated lateral and longitudinal vehicle control technology, which allow them to move in tight formation with short following distances. This study is an initial step toward developing an understanding of the occupant injury risks associated with the multiple sequential impacts between truck platoons and roadside safety barriers; regardless of whether the crash is associated with a malfunction of automated control or human operation. Full-scale crash impacts of a tractor trailer platoon into a concrete bridge guardrail were simulated for a specific Test Level condition according to the Manual for Assessing Safety Hardware (MASH) standards. The model of the bridge barrier was developed based on its drawings and material properties were assigned according to literature data. The impact simulation of the first impact was validated against a full-scale crash test conducted by the Midwest Roadside Safety Facility (MwRSF) based on resulting vehicle kinematics. Then, a higher-fidelity truck cabin model including interior structures was used to evaluate the occupant dynamics and associated safety risks during the impact event. The injury risks of the truck occupants were evaluated using Hybrid-III (HIII) and Thor dummy occupant models representing a 50th percentile male. The occupant risks of injury calculated at body region level or overall showed low injury probabilities for vehicle occupants. The motions of the dummy model and the injury risks results suggested that the 3-point seatbelt system employed in this study provided good protection for vehicle occupants in this impact scenario. Simulations with the Finite Element (FE) models developed in this study could help to understand the effectiveness of roadside safety device improvements and the necessity of platooning constraint modifications before utilization of truck platooning.

Keywords*: Occupant Injury Assessment; Finite Element Modelling; Impact Biomechanics; Occupant Protection; Road Safety Hardware*

1. Introduction

Recently, a new technology called Cooperative Adaptive Cruise Control (CACC) was developed for improving safety of vehicles following at small inter-vehicle spacing using distance measurement among inter-connected vehicles[1]. Truck platooning is a CACC extension to trucks that uses automated lateral and longitudinal vehicle control while moving in tight formation with short following distances. As technology develops and legislation permits, it is expected a gradual decrease of human involvement from current platoons with fully engaged drivers up to driverless platoons [2]. The impacts of CACC platooning have been mostly analyzed on increasing traffic efficiency in terms of road capacity[3], fuel efficiency[4] and traffic flow stability[5]. A few studies have also analyzed the safety of CACC systems in terms of reducing rear-end collisions risks on freeways [6, 7]. However, based on our knowledge, the capacity of existing roadside safety hardware to resist multiple impacts resulting from a malfunction of the automated control system or human operation have not yet been analyzed. In addition, the occupant injury risks associated with such impacts were previously unknown.

In this study, a novel method was developed to numerically simulate multiple sequential impacts of tractor trailers into a concrete barrier corresponding to a truck platooning accident. Full scale crash finite element (FE) simulations, employing an existing tractor trailer model and a detailed model of a concrete bridge system, were setup according to the Manual for Assessing Safety Hardware (MASH) standards for a specific Test Level condition. The vehicle stability and barrier damage were evaluated based on these full scale simulations. Then, the injury risks of truck occupants involved in an errant truck platooning crash were evaluated using the Hybrid-III and THOR dummy occupant models and a truck cabin model including the interior structures. In the future, additional roadside barrier systems, such as less costly systems, could be evaluated using the methodology presented in this study.

2. Methods

The overall approach to assess the occupant injury risks during a truck-to-roadside barrier impact is illustrated in Fig 1. The barrier performance and vehicle stability during full tractor trailer-barrier impacts were assessed by FE simulations. A hybrid platooning of five trucks, with occupants (drivers) in the leading truck and the last truck, was simulated [2, 8]. A cabin-only model with interior parts and a seated dummy was developed to assess the occupants' injury risks. This approach reduces the computational costs and avoids numerical instabilities associated with very large models. Detailed information about this method is provided in the next sections.

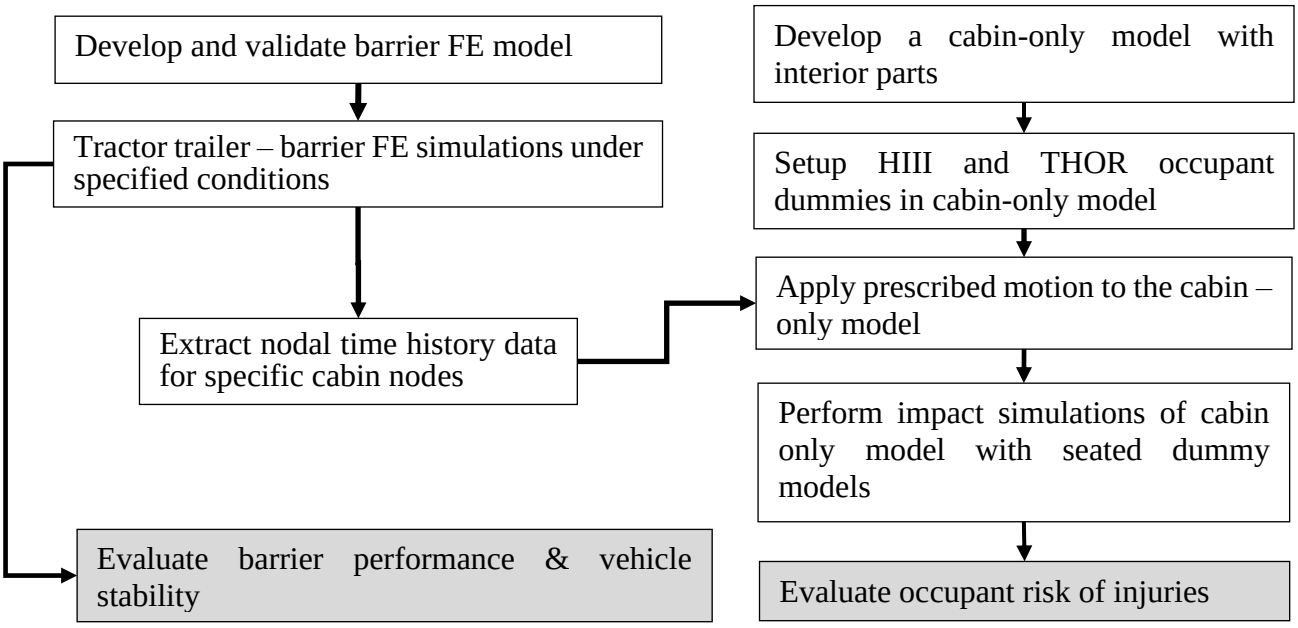

Figure 1. Overall Research Methodology

2.1. Development of the finite element models of the longitudinal barriers

Roadside safety devices are designed to reduce the speed of impacted vehicles and prevent their impact with fixed objects along the road, reducing the injury risks for vehicle occupants. To evaluate the vehicle crashworthiness, tractor trailer tests were incorporated from the Manual for Assessing Safety Hardware (MASH) in Test Level 5 (TL5) and Test Level 6 (TL6) impacts [9]. Flexible systems, such as guardrails, are not designed to preserve their protective capacity after the first impact. However, other systems such as bridge rails are usually conservatively designed for the anticipated impact loads, so they may provide some protection to errant truck platoons. As a first initial step, the impacts to TL5 bridge rails and TL5 median longitudinal barriers were evaluated in this study. The Manitoba Constrained-Width, Tall Wall Barrier tested at Midwest Roadside Safety Facility (MwRSF) was selected as a representative bridge rail [10] and the FE model was developed accordingly.

The structure of 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.). The material for the test installation of the bridge rail and deck include concrete mix with 28-day compressive strength of 45 MPa (6,500 psi) and steel reinforcement consisting of Steel Grade 400W Canadian Metric Rebar [10]. To simulate a joint in the bridge rail and deck, the Manitoba barrier was designed as two segments – upstream and downstream, with a 168 mm gap between the segments. 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. During the crash testing, the tractor trailer impacted just upstream from the simulated joint in the bridge rail.

Transverse 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) to make sure that the interior section of the barrier could also withstand the impact during the crash test [10].

The finite element (FE) model of a Manitoba barrier (Figure 2) was developed in LS-Dyna (LSTC, Livermore, CA, USA) based on the drawings of the test installation. 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. Solid brick elements (50 mm x 50 mm) of constant stress 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 [11]. The Young's modulus was 200,000 MPa (29,000 ksi), Poisson's ratio was 0.3 and yield strength was 400 MPa (58 ksi). A 20% failure strain threshold was specified using element elimination for rebar bars. The constraint of reinforcing steel in concrete was implemented using a CONSTRAINED_BEAM_IN_SOLID (CBIS) card [11]. The concrete elements were modeled using a MAT_CSCM_CONCRETE (MAT_159) [11] with a compressive strength of 45 MPa (6,500 psi). A failure elimination approach defined by a MAT_ADD_EROSION card was used for failure of the concrete model [11]. Effective plastic strain criterion of 9.45% [12] replicated the reasonable concrete erosion observed in the MAN-1 crash test as a result of multiple simulations with various parameters.

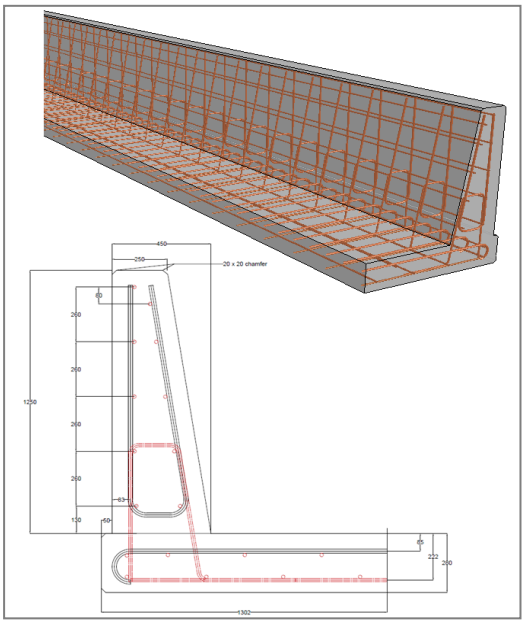

Figure 2: Cross-Section and Layout of Manitoba Barrier FE Model (dimensions in mm)

2.2. Simulations of full truck to barriers impacts

To simulate the tractor-barrier impact, an existing Texas Transportation Institute (TTI) proprietary tractor trailer FE model was utilized. This FE model was initially developed by the National Crash Analysis Center (NCAC) [13-15] , and then further improved and validated in impact scenarios by TTI. The main TTI improvements included the geometry, mesh size, connections, material properties, and suspension model. The overall length of the trailer was 14.63 m (48 ft.) and the

tractor length was 6.5 m (21.2 ft.). The tractor trailer model had 583 parts and 378,901 elements. The weight of ballasted tractor trailer was 36,170 kg (79,741 lbs.).

The pre-impact configuration of the tractor trailer model is presented in Figure 3. Appropriate contacts between truck parts and concrete/reinforcement were defined with the friction coefficients between the truck tires and the barrier, the truck body and the barrier, and the truck tires and ground of 0.45, 0.2, and 0.85, respectively [11]. Five impact simulations were performed successively using this configuration. During the simulations, the stresses and displacements of the impacted barrier were recorded in ASCII files called "dynain" [11] and used in the following truck-barrier impact simulations. In a real errant truck platooning accident could be complex and may involve impacts between trucks as well. In this study, the worst safety condition for the barrier was simulated, when it is impacted at the same location by all five trucks in the same pre-impact configuration.

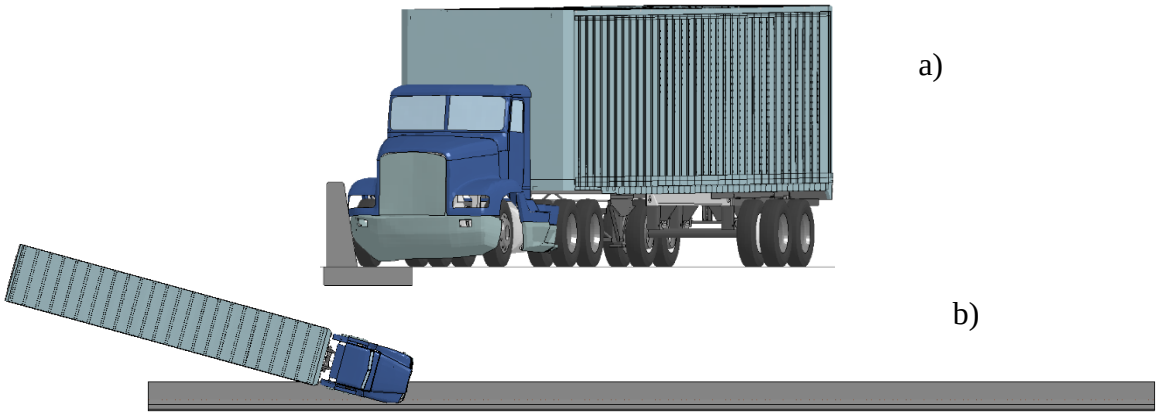

Figure 3: Front (a) and Top View (b) of tractor trailer at the beginning of impact

2.3. Development of finite element model of truck cabin used in occupant injury risk assessment

The cabin part of the tractor trailer finite element model was extracted and further used to develop the cabin-only model. The interior cabin parts were not included in the original full tractor trailer model, so the seats and the steering column system from another truck FE model were used. The material models of the interior parts were defined based on similar data from publicly available FE vehicle models or in-house material data [16, 17].

The motion of the cabin-only model was prescribed using the displacement time histories of 8 nodes recorded in the tractor trailer during full scale barrier impact FE simulation. Four of the nodes were located on the cabin floor and the other four nodes are located on the cabin roof (Fig. 4a). The selected nodes were selected to be symmetrical about the longitudinal axis of the cabin. To verify the accuracy of the cabin-only model motion, four nodes (other than the nodes used in prescribed motion -Fig. 4b) were selected and their displacement time histories were compared with the same nodes of the full tractor trailer model.

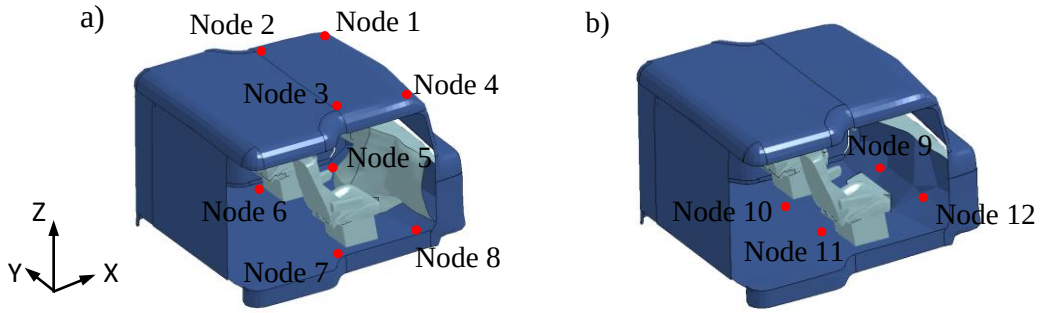

Figure 4. a) The locations of prescribed motion points in the cabin-only model b) The locations of nodes used to verify the cabin motion.

To assess the occupant injury risk, the Hybrid-III and the THOR dummy models [16, 18-20], the most widely employed frontal automotive dummies, were placed within the cabin-only model. The FE model of the Hybrid-III dummy used in this study was provided by LSTC (Livermore, CA, USA)[21]. The Hybrid-III model consists of 367 parts, 276,025 nodes and 451,769 elements, and it was validated at component level against various certification test data (e.g. neck extension/flexion, thorax impact). The FE model of the THOR (Test device for Human Occupant Restraint) dummy was developed by NHTSA and their collaborators [22] and updated according to recent modifications [18, 19]. The THOR FE model consists of 222,292 nodes and 444,324 elements. Similarly, the THOR FE model was validated by CIB-VT computational group against component certification test data [16, 18, 19].

A single occupant dummy model was positioned in the driver's seat with hands holding the steering wheel, and feet placed on the floor [23]. The setup for both dummy models used the same standard three-point belt seatbelt system[24], developed based on LSTC seatbelt model (Fig. 5).

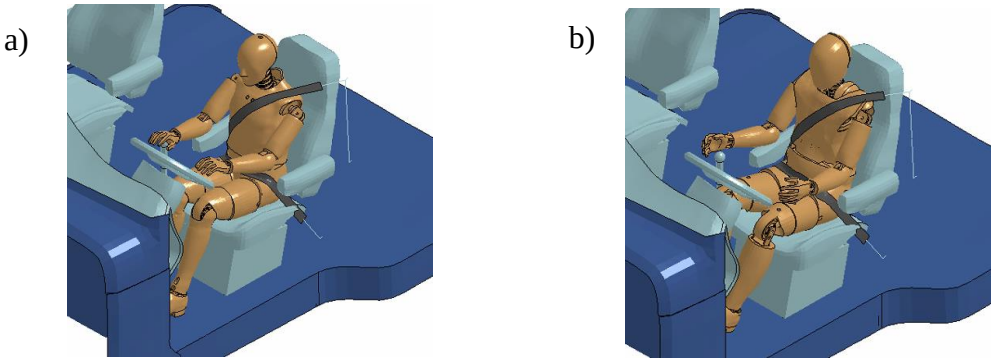

Figure 5. Occupants models seated inside the simplified cabin model a) Hybrid-III dummy model b) THOR dummy model

Initially, a pretensioner model was fired at the first contact of the truck and barrier model. However, it was found that the occupant seat lateral (y-direction) acceleration due to offset impact with the barrier model started to increase after 0.2s (Fig. 6).

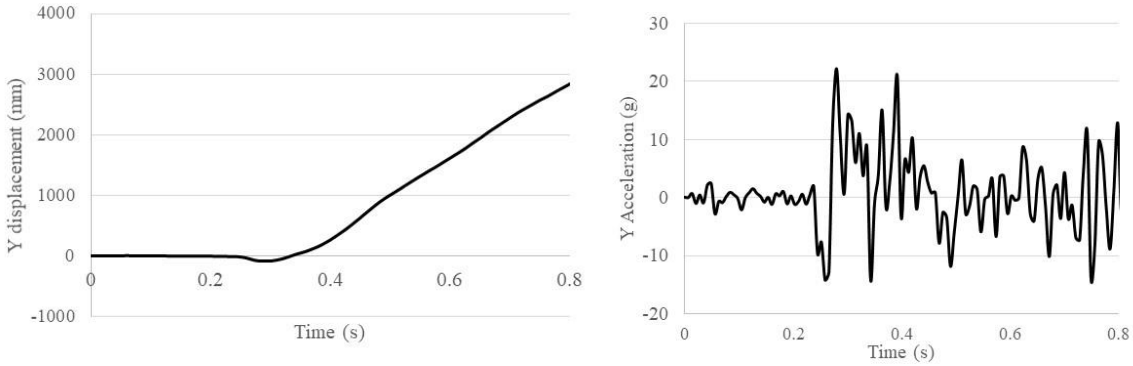

Figure 5. The time histories of displacement (a) and acceleration (b) recorded at the floor node 11.

To reduce the computational effort, the beginning of impact (first 0.2 s) was not simulated, so the pretensioner system was not activated. However, the seatbelt system was setup in a configuration close to a post-firing configuration. For example, the seatbelt elements were defined as zero initial slack length with 3 mm minimum length and the webbing fed length in retractor was 10 mm. The friction coefficients in seatbelt - D-rings and dummy-seatbelt contacts were defined as 0.1 and 0.4, respectively. The restraint system included also a frontal-airbag system which was turned off to evaluate the effectiveness of the belt system. It should also be mentioned that airbag systems are not commonly installed in medium/heavy trucks being non-mandatory[25, 26].

2.5. Assessment of truck occupants' injury risks involved in a truck platoon-barrier crash

The kinetic and kinematic responses of dummy FE models recorded during impact simulations were used to calculate injury criteria (Appendix A) to various occupant body regions[27-29]. Then, these measures were compared to the injury assessment reference values (IARVs) and Abbreviated Injury Scale (AIS) to assess the occupant injury risks. 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 (Table 1). Acceptable ratings correspond to measures below the IARVs indicated in the table below.

Table 1 Injury Parameter Cutoff Values Associated with Injury Protection Ratings (50th male)

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

3. Results and Discussion

3.1. Barrier Performance

The full scale tractor trailer- barrier simulation was performed corresponding to the MAN-1 test [10], with the pre-impact tractor speed of 83.2 km/h (51.7 mph) at an angle of 15.2 degrees relative to the barrier. According to the simulation results, the tractor-trailer struck the barrier approximately 10.52 m (34.5 ft) from the upstream barrier end and was successfully contained and redirected by the barrier (Fig. 7). The barrier experienced a 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[10]. The permanent nodal displacement of the barrier from the impact was 44 mm (1.73 in).

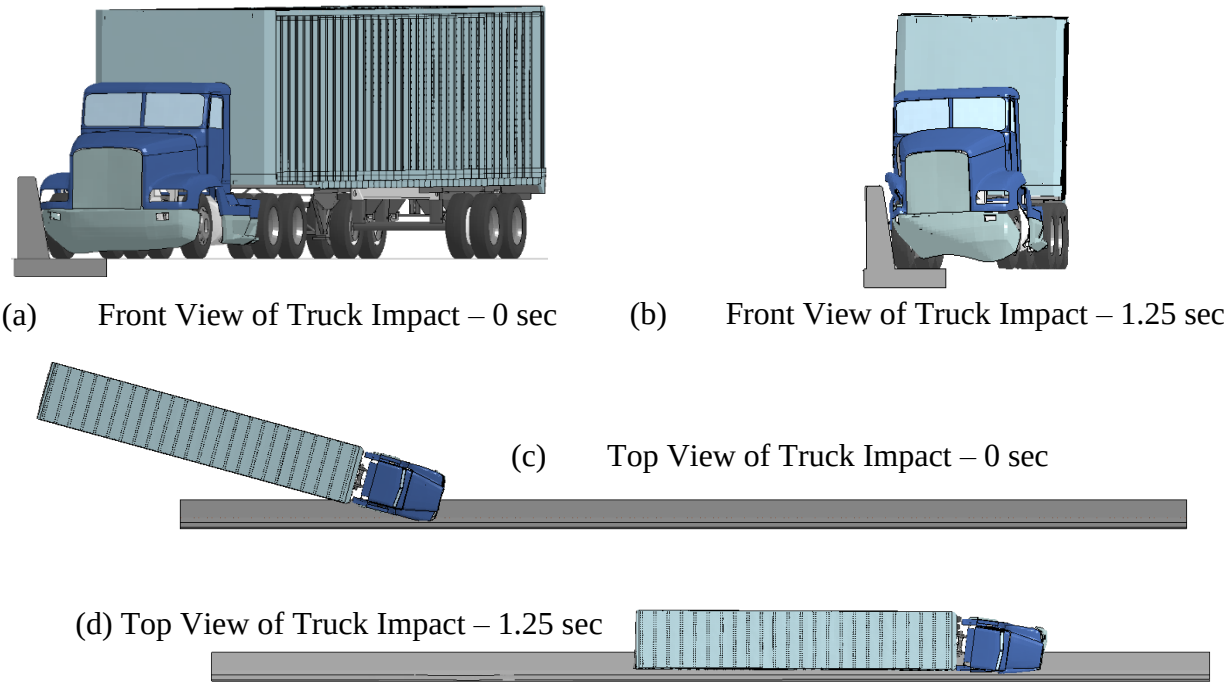

Figure 7: Impact (at 0 sec) and Intermediate (at 1.25 sec) Positions of the Manitoba Barrier

In terms of barrier damage, erosion at the top of the barrier (Fig. 8) occurred 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, and a line of second-to-top layer of elements also was eroded on the front side. At the areas where the concrete strain values were the highest, potential cracks could be found.

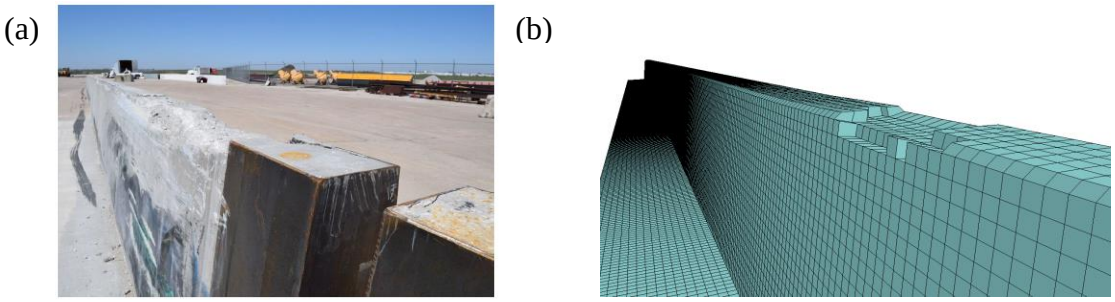

Figure 8: (a) MAN-1 Crash Test – Barrier Damage vs (b) FE Simulation

The maximum plastic strain of about 5% was observed in transverse rebar in a very small region at the top of the barrier where the concrete erosion occurred. In addition, most of the reinforcement had negligible or no plastic strain. Minimal damage occurred on 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 [10].

The design of the Manibota barrier in this study was shown to be reliable enough to prevent rollover during the impact event, and the stability of vehicle was also guaranteed [30]. The damage to the barrier was small, only about 5% maximum plastic strain, and was observed only in a very small region at the top of the barrier where the concrete erosion occurred. For the most part of the reinforcement, negligible or no plastic strain was observed.

3.2. Vehicle Stability

The physical tractor and the FE tractor model were both stable during the impact events without rollover (Fig. 9 and 10). During the impact simulation (2 sec after initial impact), about 20% of the tractor's initial kinetic energy was dissipated in the form of sliding interface energy. Similarly, the amount of initial kinetic energy converted to internal energy was about 5%. In addition, the hourglass energy of the system was less than 1%.

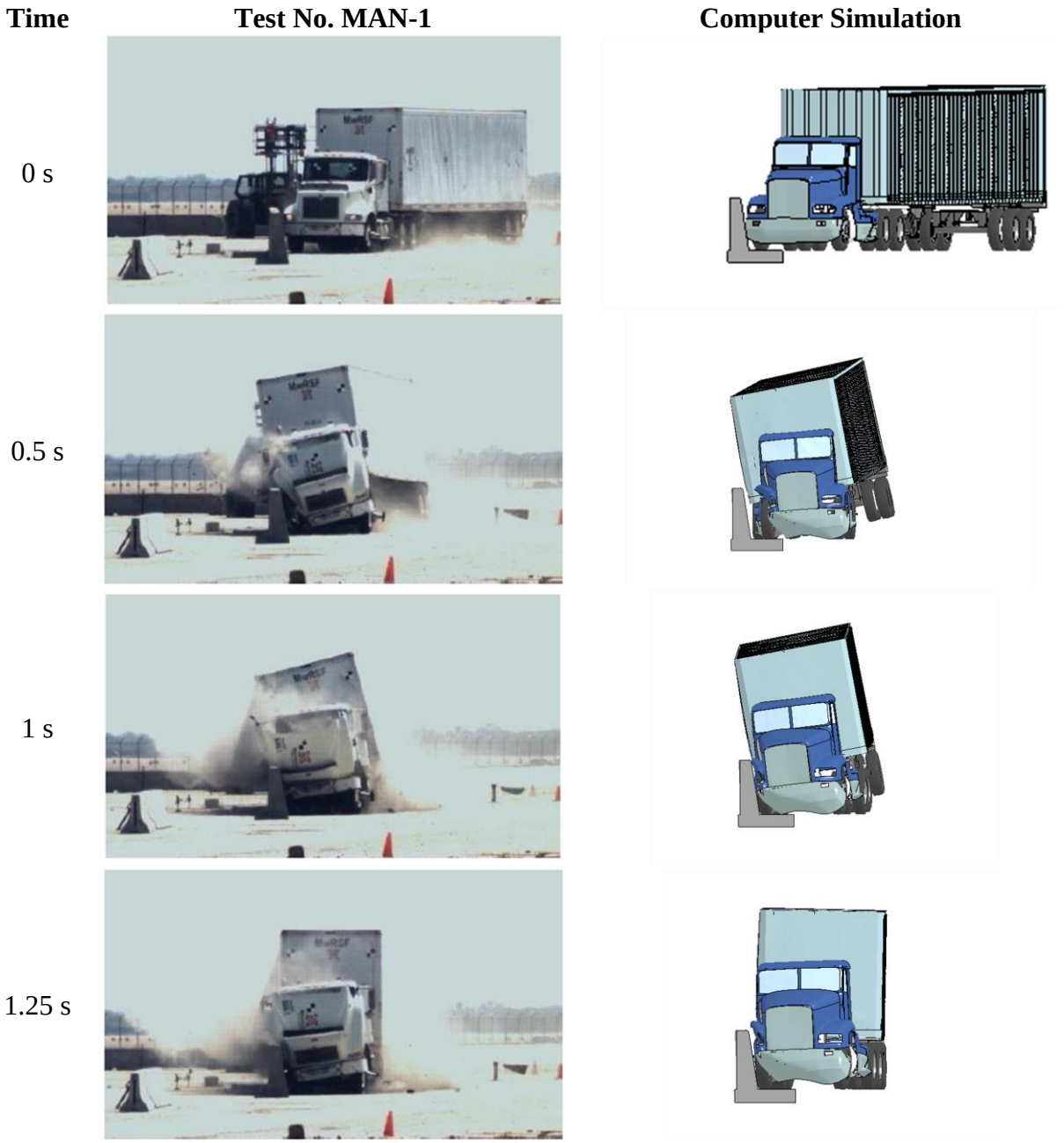

Figure 8: Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Front View (Rosenbaugh et al., 2016)

Figure 9: Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Front View (Rosenbaugh et al., 2016)

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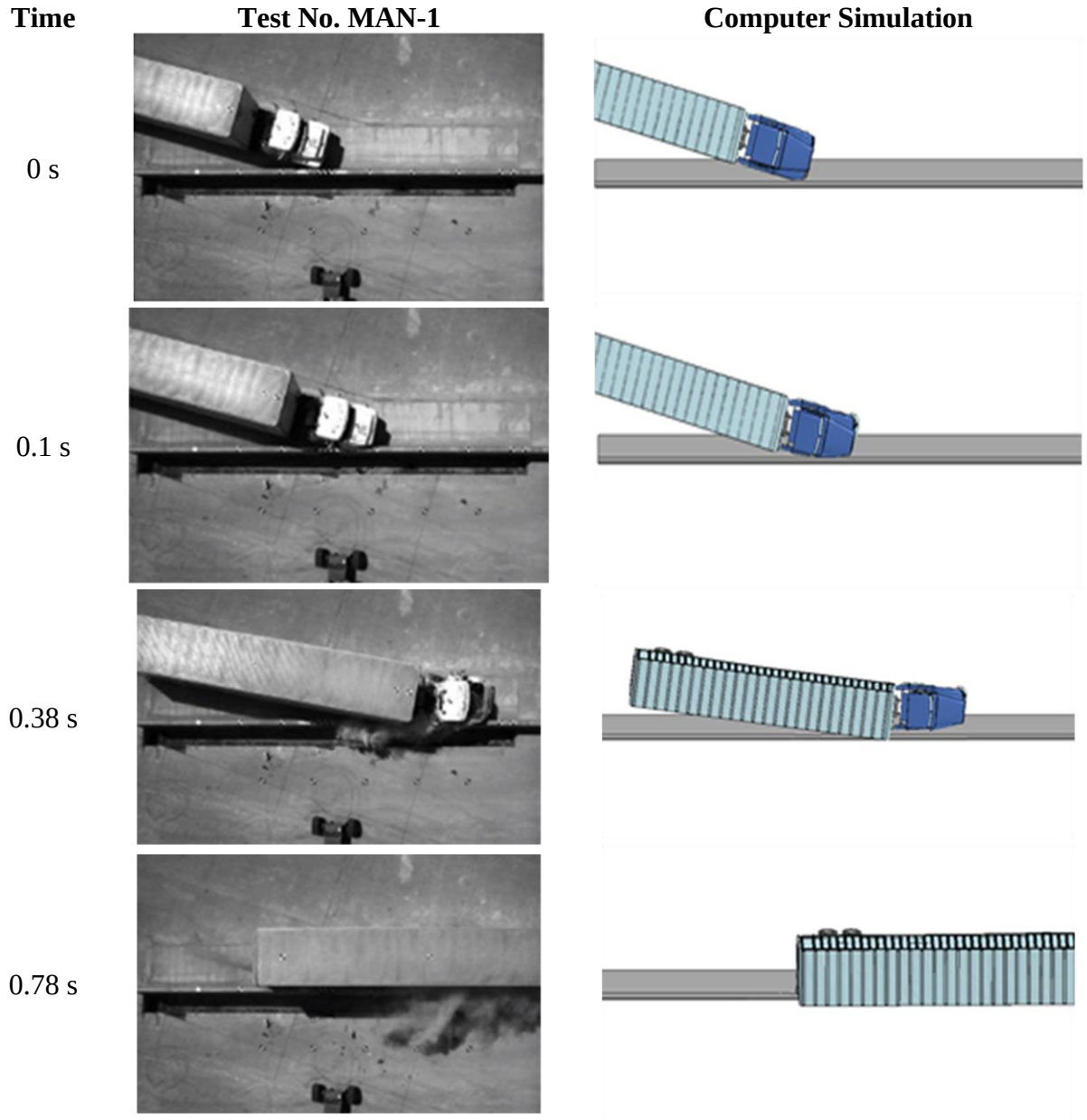

Figure 9: Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Top View (Rosenbaugh et al., 2016)

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

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3.3 Assessment of tractor occupants' injury risks involved in a truck platoon-barrier crash

The assessment of tractor occupants' injury risks involved in a truck platoon-barrier crash was performed using the cabin only model, which included interior parts and dummy models. The overall kinematics of this cabin-only model showed to be similar to the kinematics of the full tractor trailer. The displacement differences of the four nodes randomly chosen were very low in horizontal (x/y) direction (less than 5mm), and slightly higher in vertical (z) direction (under 1.7 cm). Therefore, the cabin only model was then used in the occupant injury assessment. Generally, in both simulations with HIII and THOR dummies, the seatbelt system was able to effectively protect the occupant, thus no impacts between the dummy and other interior tractor parts (except the seat) were observed. (Fig. 11).

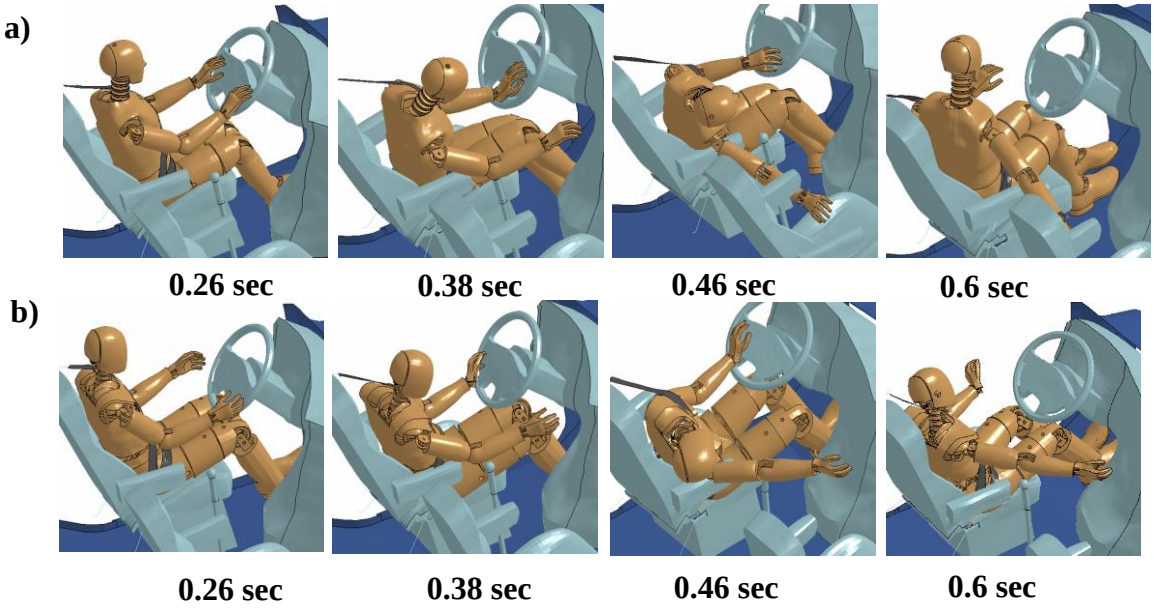

Figure 11. Motions of occupant models during 1st tractor impact, a) Hybrid-III dummy model b) THOR dummy model

Although some differences are observed in dummy kinematics between Hybrid-III and THOR dummy models, possibly caused by different interactions with the seat belt, the predicted values of injury criteria were close (Table 2). Overall, the impact scenario based on the MAN-1 test showed to be much less aggressive than a typical front crash scenario, which resulted in a very low injury risk for truck occupants.

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

Occupant Model	Impact #	Head HIC-15	Neck N_{ij}	Chest Chest Deflection	Femur Femur Axial Force
Hybrid-III (value/injury probability)	1st	81.2 / 0.00%	0.40 / 8.02%	11.40 mm / 4.03%	845.366 N / 0.90%
	5th	18.9 / 0.00%	0.23 / 5.87%	7.71 mm / 3.40%	684.85 N / 0.85%
THOR (value/injury probability)	1st	135.7 / 0.03%	0.47 / 9.10%	28.52 mm / 1.36%	574.18 N / 0.82%
	5th	124.1 / 0.02%	0.38 / 7.74%	17.28 mm / 0.10%	510.71 N / 0.81%

The maximum values of injury criteria recorded during the crash simulation showed to be well below the IARVs values, which suggested very low injury risk for truck occupants. Three injury values (HIC, chest deflection, and femur axial forces) were less than 20% of IARVs. The larger displacement of upper body during the impact event may cause the increased risk of neck injury compared to other body parts. For the same reason, chest injury probability is the second highest among all four body regions covered in this study, whereas, it is still relatively low (less than 4% for two dummies). In addition, the 1st impact and the damage to the barrier from that impact were reflected in the outcome of the 5th impact for occupant injury risk evaluation. The values of injury criteria for the drivers of the 5th tractor (the last of the platoon) were lower than the drivers of the 1st tractor caused by a soften pulse generated by the barrier which suffered 5 consecutive impacts. As long as the barriers are reliable, the occupant injury risks are limited for truck platooning. The predicted Occupant Injury Measure (OIM) (Appendix A) from both dummy models were lower than 15%, which corresponds to relatively low injury risks for occupants. The predicted OIM results from both dummies are also very close (Table 3), which proved the effectiveness of both dummies to be used in the injury assessment.

Table 3. Occupant Injury Measure

OIM	Value (1st / 5th Impact)
Hybrid-III	12.52% / 9.84%
THOR	11.07% / 8.76%

While this study is the first attempt to evaluate the occupant safety during truck platooning impact, it has also several limitations that should be acknowledged. The Manibota barrier model developed in this study was validated only to the first impact, so validations to sequential impacts should be performed in the future when test data will be available. More validations of the tractor model, which should cover the failure of their parts, are recommended. This will allow to evaluate to what extent the wreckage of the trucks preceding the last truck would present an additional and possibly more severe hazard to the operator of the last truck. In this study, dummy models were positioned in a nominal/standard driver pre-impact posture, but various out-of-position pre-crash occupant postures are expected in future automated trucks. Therefore, to have a better

understanding of the injury risks associated with the tractor occupants after veering off the platoon course, more impact simulations should be performed under pre-impact scenarios (e.g. vehicle impact direction/ impact velocity, driver posture) varied in a parametric fashion (e.g. using DOE). Finally, in addition to HIII and THOR ATD models used in this study, human models with different anthropometries, such as Global Human Body Modelling (GHBMC) models [31-34], are recommended to be utilized in future.

4. Conclusions

An errant truck platooning impact event was studied using a detailed reinforced barrier and deck model. The performance of the developed barrier FE model was evaluated using the initial impact and then used in successive truck impacts corresponding to a five-truck platoon. From the simulation results, the designed road safety hardware was able to contain and redirect the impacting vehicle without rollover. Hybrid-III and the THOR dummy FE models were utilized to assess the injury risk for truck platooning occupant drivers. To reduce the computation cost, a simplified cabin FE model with interior components was developed and verified with full scale tractor trailer motion data. A 3-point seatbelt restraint system was developed for the cabin-only FE model to protect the occupants. The injury risks of the vehicle drivers during the barrier impact were relatively low, which suggested that regular seatbelt system was able protect the occupants in this kind of impact. The methodology presented in this study could also be applied to simulate various impact scenarios from errant truck platoon accidents.

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Appendix A. Injury risk prediction and the calculation of the whole-body injury metric

Abbreviated Injury Scale (AIS), created by the Association for the Advancement of Automotive Medicine (AAAM), is defined to classify the probability of injury and describe the severity of individual injuries. AIS also represents the threat to life associated with the injury rather than the comprehensive assessment of the severity of the injury [35, 36]. While descriptions of the injury criteria used in this study are briefly introduced, the more detailed treatment is referred to literature [36, 37].

A.1. Head Injury Criteria (HIC)

The head injury criterion (HIC) is defined on the basis of the head acceleration. In the Hybrid-III and the THOR dummy FE model, the HIC is recorded by nodal output of acceleration from the center of gravity of the head. HIC15 value are exported from the simulation results which defined as follows:

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

The probability of head injury (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).

A.2. Neck Injury Criteria (N_{ij})

Neck injury criteria are defined 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 of force and moment. 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 Nm. The probability of neck injury (AIS⩾3) is given by the formula

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

A.3. Injury Criteria - Thoracic

Chest deflection relative to the sternum during impact event is used to calculate chest injury probability. *Dmax* is the maximum value of the dummy deflection (*D*). In the Hybrid-III dummy model, the chest deflection is obtained by using a rotary potentiometer; in the THOR dummy

model, the chest deflection is achieved by measuring nodal distances for both the left chest and right chest. As a result, different probability formula of chest injury (AIS⩾3) are defined for the two dummies. For the Hybrid-III dummy

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

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.

A.4. Injury Criteria - Femur

The risk of femur injury were defined based on the maximum axial femur loads. 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.

A.5. Occupant Injury Measure (OIM)

Occupant Injury Measure (OIM), proposed in the CAMP-ARS study [36], was used to define the overall injury risk, which was calculated by summarizing the individual AIS3+ Injury risk probabilities of each injury risk value.

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