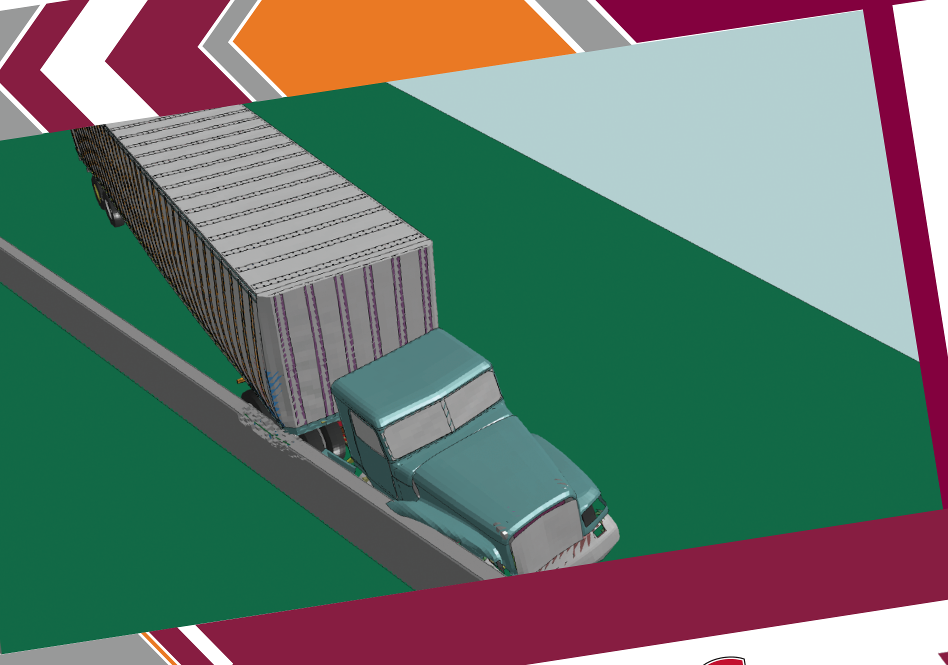
Implications of Truck Platoons for Roadside Hardware and Vehicle Safety

October 2019 | Final Report



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Abstract

Platooning is an extension of cooperative adaptive cruise control and forward collision avoidance technology, which provides automated lateral and longitudinal vehicle control to maintain short following distances and tight formation. The capacity and adequacy of existing roadside safety hardware deployed at strategic locations may not be sufficient to resist potential impact from an errant fleet of multiple trucks platooning at high speed. It is unknown how these impacting trucks might interact with roadside safety barriers after leaving their platoon and what the occupant risks associated with such impacts may be. This research identifies and prioritizes the critical Manual for Assessing Safety Hardware TL5 roadside safety devices for truck platooning impact assessment in order to understand the associated roadside and occupant risks and hazards. Finite element models of the trucks and roadside safety devices are examined using multiple computer simulations for various scenarios. Occupants injury risks during truck collision simulations are assessed using dummy and human finite element models. The results and implications can provide a better understanding of whether any roadside safety device improvements and/or platooning constraint modifications will be necessary before implementing truck platooning.

Acknowledgements

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Introduction

Platooning is an extension of cooperative adaptive cruise control and forward collision avoidance technology that provides automated lateral and longitudinal vehicle control to maintain short following distances and tight formation. A manually driven truck leads the platoon, allowing drivers of the following trucks to disengage from driving tasks, though they must remain alert and monitor the performance of the system. As platooning is a new technology, it is necessary to understand whether existing roadside safety devices are adequate for resisting potential multiple impacts due to errant truck platoons. It is also important to know how errant platoons might behave, as well as the associated occupant risks and risks to other motorists during and after such impacts.

The objectives of this research are:

a. to assess, via computer simulations, the structural adequacy of the selected critical roadside devices in the event of errant truck platoon impacts;
b. to assess the stability of the impacting trucks;
c. to assess risks imposed to occupants using finite element (FE) models of anthropomorphic test devices (ATDs).

Background

Truck-platooning is a long-term vision to improve the freight system while maintaining roadside safety and increasing "team" fuel efficiency by up to 6.4% [1]. Research and development on autonomous trucks and platooning began as early as the 1990s; however, most major progress in platooning has been made in the past 5 years [2]. Autonomous technology is new, still considered largely in the development phase, in both the U.S. and in Europe. Platooning is ideal for trucks, as they usually travel long distances on high speed roadways in groups. The Federal Highway Administration (FHWA) and the Texas Department of Transportation intend to deploy commercial two-truck platoons at specific routes in Texas within a decade [3]. Considering the limited progress that has been made in platooning technology itself, there has been no research to date on the impact of truck platoons colliding with roadside devices or the associated risks to their occupants and/or other motorists during such impacts.

While there has not been significant research into the impact of truck platoons colliding with roadside devices, there has been extensive research into the impact of single tractor-van collisions with roadside devices and the associated risks to occupants and other motorists. National Cooperative Highway Research Program Report 350, published in 1993, previously contained the criteria for designing roadside safety devices. That report was replaced by the Manual for Assessing Safety Hardware (MASH) in 2009 [4,5]. Criteria defined in MASH 2016, which superseded MASH 2009, were the basis for developing the impact scenarios in this research [5]. The impact criteria for MASH Test Level 5 (TL5) include the impact of a 36,000 kg (80,000 lb) tractor-van trailer at an angle of 15 degrees and speed of 80 km/h (50 mph). TL5 test criteria are for large trucks on high speed highways, freeways, and interstate highways where many large trucks are present. Unfavorable site conditions can also exist on these types of roads, which may lead to rollover or penetration beyond the railing, for instance, potentially resulting in severe consequences [17]. In truck platoons, the following trucks are controlled by vehicle-to-vehicle communication, the malfunction of which needs to be studied to understand the possible impact scenarios.

The occupant injury risks resulting from errant truck platooning impacts could be different than injury risks from regular single vehicle impacts. Only the first and last trucks in the platoon have active drivers (i.e., are not autonomous). While several studies related to occupant injury risks for traditional heavy trucks [26-28] have been carried out, there is still a need for further investigations of truck platooning impact scenarios.

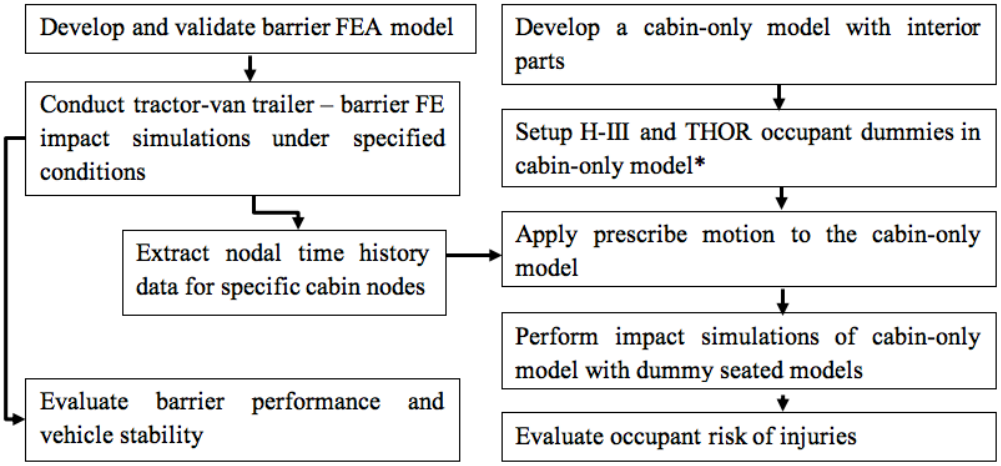
Structural adequacy, vehicle stability and occupant risk are the main criteria for the evaluation of roadside devices. Finite element analysis (FEA) programs serve as an important tool in evaluating these criteria. To execute this study, the authors used LS- DYNA, one of the most popular explicit FEA software codes in the roadside safety field [6]. It is capable of analyzing the non-linear dynamic response of three-dimensional structures and has been used extensively in vehicle crashworthiness simulations.

Method

Figure 1 shows the overall approach followed to complete this collaborative effort between Texas A&M Transportation Institute (TTI) and Virginia Tech Transportation Institute (VTTI). The TTI team carried out the evaluation of barrier performance and vehicle stability with a full tractor-van trailer model, whereas the VTTI team assessed occupant injury risks using a cabin-dummy-only model with interior parts and dummy models. A cabin-dummy-only model, driven by applying prescribed motion to the cabin nodes recorded in full tractor-barrier simulation, was preferred over a full tractor-van model with interior and dummy. This approach was chosen not only for proprietary reasons but also because it restricted the computational costs and avoided numerical instabilities associated with very large models.

First, categories of roadside safety devices were prioritized for evaluation based on their application and identified potential risks to motorists. MASH incorporates tractor-van trailer tests in TL5 impacts, so roadside safety devices under other test levels were not considered for this study [5]. 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 concrete bridge rails and TL5 rigid concrete median barriers were identified as the most appropriate roadside safety features for impact assessment. A list of non-proprietary TL5 barriers, with eligibility letters from the FHWA, was reviewed. For this study, the Manitoba Constrained-Width, Tall Wall Barrier (Test No. MAN-1, FHWA B-268) and the

Vertical Faced Concrete Median Barrier (Test No. TL5CMB2, FHWA B-182) tested at Midwest Roadside Safety Facility (MwRSF) were selected as a representative concrete bridge rail and concrete median barrier respectively [7,8].



*H-III = Hybrid III; THOR = Test device for Human Occupant Restraint

Figure 1. Overall research methodology.

The kinematic response of the FEA vehicle was in good agreement with the full-scale crash test vehicle, and the phenomenological events from the full-scale crash test were well replicated by the FEA for both tests. The leading truck impact simulations were quantitatively evaluated against the respective full-scale crash tests for both the Manitoba concrete bridge rail and the concrete median barrier following the Roadside Safety Simulation Validation Program (RSVVP) guidelines [9, 10]. System descriptions and validations for the Manitoba concrete bridge rail and the concrete median barrier are reported in Appendix A and Appendix B respectively.

Considering feasibility and computational costs, separate simulations were run in series to simulate the impact of each truck involved in the platoon against the selected roadside barrier. The first simulation—the leading truck impacting the barrier—was used to output a DYNAIN file, which stores the stresses and displacements of the impacted barrier at the end of the simulated impact event [6]. Those stresses and displacements were defined as the initial conditions of the barrier for the following truck impact. The same procedure was used to define the initial conditions for the following impacts. As there has been no substantial research on the behavior of errant truck platoons, there is no known data on the angle and speed at which the following errant platoon trucks will impact the roadside barriers. So, the impact conditions (speed, angle and location) defined by MASH for TL5 impacts were used for the following truck impacts as well.

Within MASH criteria, the flail space model concept is utilized to assess occupant risk [11]. In full-scale crash simulations, the data required for occupant risk assessment—based on theoretical flail space model concept of an unrestrained point mass—were collected by TTI team from the accelerometer modeled at the vehicle's center of gravity. The VTTI team performed extensive and better predictive occupant risk assessment was using ATDs, which show humanlike response and can predict potential injuries to various regions of the body.

To reduce the simulation time for occupant risk assessment, a cabin-only FE model was developed based on an original tractor-van trailer. The interior cabin parts, including the seats and the steering wheel column systems, were scaled and added from another existing cabin-over-engine FE model. The motion of the cabin-only model was prescribed based on the displacement time histories of eight nodes recorded in the tractor-van trailer during barrier impact FE simulation. Four nodes were located on the cabin floor and four nodes were located on the roof, as shown in Figure 2.

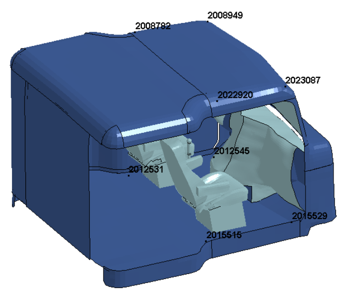


Figure 2. The locations of prescribed motion points in the cabin-only model.

The Hybrid-III and the Test device for Human Occupant Restraint (THOR) dummy models [19-21] 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, U.S.) [22]. The THOR dummy was an advanced impact 50th percentile adult ATD. This study used an FE model of the THOR that was developed by the National Highway Safety Administration and collaborators [23] and which has been updated according to recent modifications [9]. The THOR FE model was previously calibrated and validated against component certification test data by the computation group at the Center for Injury Biomechanics at Virginia Tech [19, 20, 24].

The occupant dummy models were seated, and specific FE models of the three-point seatbelt systems were developed to restrain the models on the seat. The same seatbelt system, which included a retractor, a pretensioner and two D-rings, was used for both dummy models, as shown in Figure 3. The positions of the dummies were adjusted to simulate a driver's posture with hands holding the steering wheel, and feet placed on the ground [25].

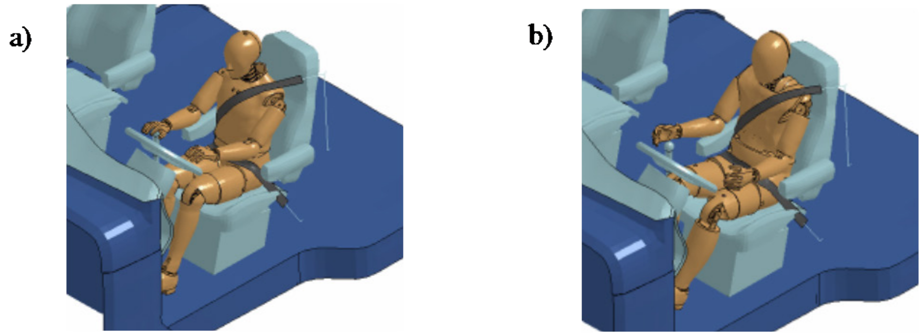


Figure 3. Occupant models seated inside the simplified cabin model a) Hybrid-III dummy model b) THOR dummy model.

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 [26, 27].

The Abbreviated Injury Scale (AIS), created by the Association for the Advancement of Automotive Medicine, classifies the severity of human body injuries based on the threat to life associated with the injury rather than the comprehensive assessment of the severity of the injury [28, 29]. For example, AIS3+ injuries are classified as serious injuries and their probability is calculated based on injury curves, which have the values of injury criteria as variables. While short descriptions of the probability of injury curves and the injury criteria used in this study are briefly outlined in Table 1, a more detailed treatment can be found in reference [30].

Table 1. Occupant Injury Criteria and Probability of Injury

Injury Criteria	Formula	Probability of Injury
Head	$HIC = \max\left[\left[\frac{\int_{t_1}^{t_1} a(t)dt}{t_2 - t_1}\right]^{2.5}(t_2 - t_1)\right]$	$p(fracture) = N\left(\frac{\ln(HIC) - \mu}{\sigma}\right)$ $\mu = 7.45231, \sigma = 0.73998$
Neck	$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}}$	$p(AIS \geq 3) = \frac{1}{1 + e^{3.227 - 1.969N_{ij}}}$
Chest	N/A	Hybrid-III: $p(AIS \geq 3) = \frac{1}{1+e^{3.7124-0.0475D}}$ THOR: $p(AIS \geq 3) = 1 - exp(-[\frac{D}{e^{4.4853-0.0113age}}]^{5.03896})$
Femur	N/A	$p(AIS \geq 3) = \frac{1}{1 + e^{4.9795-0.326F}}$

Occupant Injury Measure (OIM) was then calculated based on the values of injury probabilities corresponding to body parts (e.g. head, neck, etc.). The formulation (AIS3+) of OIM was proposed in the Crash Avoidance Metrics Partnership Advanced Restraint Systems project [31].

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

Results

Finite Element Results – Manitoba Concrete Bridge Rail

This section discusses the results of the FE simulation for the five consecutive MASH TL5 impacts into the Manitoba concrete bridge rail modeled with 1,302 mm (4.3 ft) of bridge deck width.

Barrier Performance

The barrier was impacted consecutively by five tractor-trailers at an angle of 15.2 degrees and a speed of 83.2 km/h (51.7 mph) at about 10,516 mm (34.5 ft) from the upstream end of the barrier. The barrier performance for each impact is summarized in Table 2 below [7]. The impacting vehicles were successfully contained and redirected by the barrier.

Table 2. Barrier Performance - Manitoba Concrete Bridge Rail with Deck [7]

	1st Truck	2nd Truck	3rd Truck	4th Truck	5th Truck
Maximum dynamic displacement in simulation relative to the position after pervious impact [mm (in)]	50 (1.97)	25 (0.98)	22 (0.87)	16 (0.63)	13 (0.51)
Maximum dynamic displacement in simulation from the initial position before first impact [mm (in)]	50 (1.97)	63 (2.48)	74 (2.92)	83 (3.27)	86 (3.39)
Maximum dynamic displacement in full-scale crash test [mm (in)]	52 (2.05)	N/A	N/A	N/A	N/A
Maximum dynamic displacement time (after first contact of respective vehicle to the barrier) (sec)	0.72	0.72	0.76	0.66	0.68
Permanent displacement in simulation relative to the position after pervious impact [mm (in)]	38 (1.5)	14 (0.55)	15 (0.59)	6 (0.24)	2 (0.1)
Permanent displacement in simulation from the initial position before first impact [mm (in)]	38 (1.5)	52 (2.05)	67 (2.63)	73 (2.9)	75 (2.95)
Permanent displacement in full-scale crash test [mm (in)]	0	N/A	N/A	N/A	N/A
Was the impacting vehicle successfully contained and redirected?	Yes	Yes	Yes	Yes	Yes

Energy Values

A truck impacting the barrier is a closed system and 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. The global energies data (GLSTAT) from LS DYNA include the contribution of eroded elements during the impact [12]. So, 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.

It was observed that the total energy of the system remained close to 100% during the impact period for the first through the fifth tractor-trailer impacts into the barrier. The hourglass energy of the system was less than 1% for each of the impacts. Observed conservation of energy and low hourglass energy indicated that the system was stable and that nonphysical energy modes did not affect the results. The kinetic energy at the end of each simulation was in the range of 50% to 70%; this energy was due to the remaining velocity of the impacting truck.

Vehicle Stability

Figure 4 shows the frame comparison for the truck platoon impact on the Manitoba concrete bridge rail. Due to higher angular displacements during impact, it was observed that the tractor-trailers in the third through fifth impacts took longer to stabilize as compared to the first or second impacts.

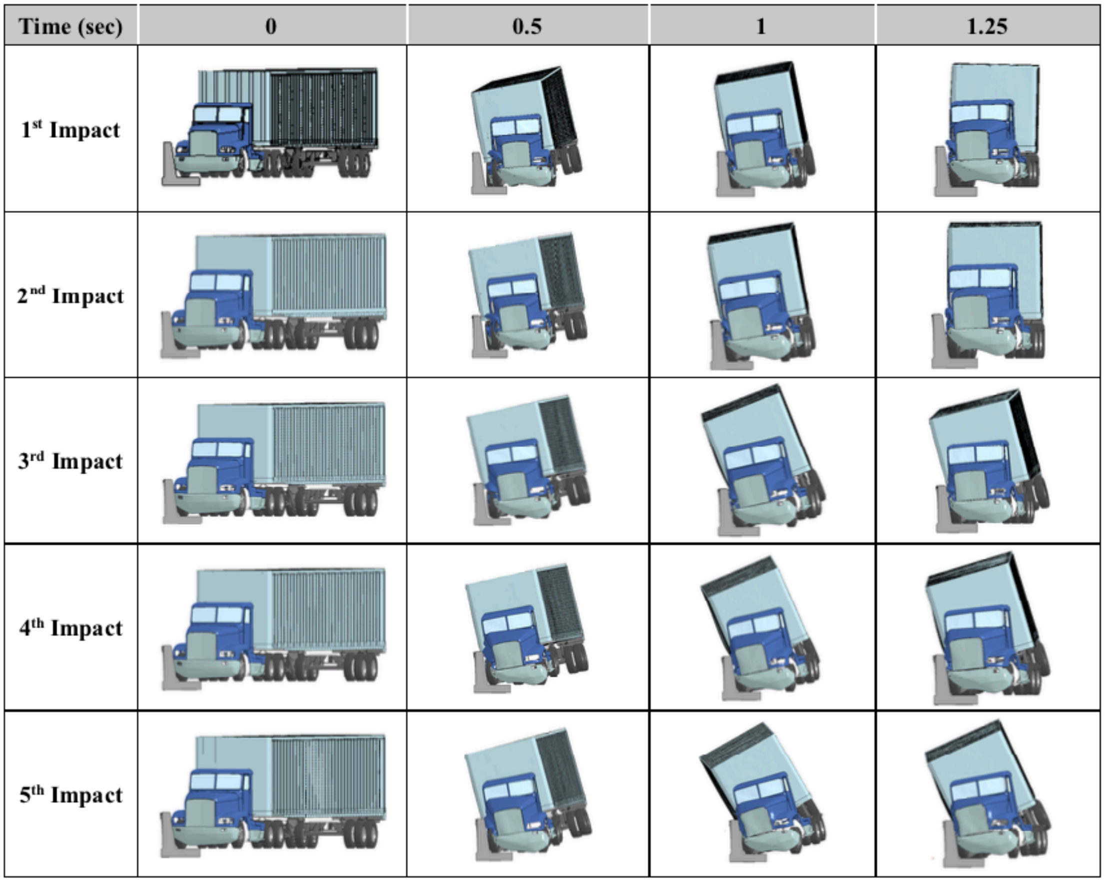


Figure 4. Frame comparison of impact simulations for Manitoba concrete bridge rail – front view

Barrier Strength

Concrete erosion and steel damage at the top of the barrier due to the impacts can be observed in and Figure 5. The erosion parameter was defined such that the elements were deleted when the effective plastic strain in the concrete exceeded 9.45%.

In the first impact, erosion occurred at the top of the barrier beginning at about 13,194 mm (43.3 ft) from the upstream end of the barrier and extending about 747 mm (2.5 ft). Almost all of the top layer of 50 mm solid elements from front side (impact side) to the back side of the barrier was eroded at the described location. A line of second-to-top layer of elements also eroded on the front side.

Additional erosion occurred at the top of the barrier now beginning at about 7,198 mm (23.6 ft) from the upstream end of the barrier and extending downstream for about 19,236 mm (63.1 ft). At the area on the front face with maximum damage, which stretched over a span of 10,090 mm (33.1 ft), up to nine top layers of 50 mm solid elements were eroded and about 26 lateral rebar top ends were exposed and damaged. A maximum of seven top layers of solid elements were eroded on the back face of the barrier.

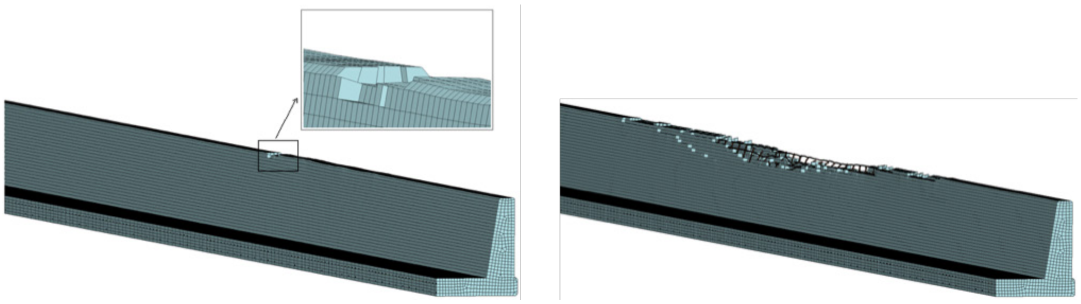


Figure 5. Erosion of Manitoba concrete bridge rail – first impact (left) and fifth impact (right).

Figure 6 shows the plastic strains in the steel reinforcement of the barrier at the end of first and last impact. The steel reinforcement, modeled as beam elements, was not considered in the calculations if the maximum plastic strain exceeded 20%. Reinforcement in navy blue represents negligible or no plastic strain. At the end of the first impact, maximum steel plastic strain of 5% was observed; the damage was in a small region at the top of the barrier. At the end of the fifth impact, elements at the top end of about 20 traverse lengths of rebar failed based on 20% maximum plastic strain criteria. At least 8,843 mm (29 ft) segments of two longitudinal lengths of rebar at the top-front end of the barrier were damaged or fully exposed due to concrete erosion.

Erosion of the solid elements in the deck, representing deck concrete failure, was not observed in the simulations. However, near the point of impact, the effective plastic strain values were very close to 9.45% along the deck-barrier interface and constrained end of the deck, extending a length of about 12 m (39.4 ft). Cracks are likely to occur at these regions during the full-scale impact test.

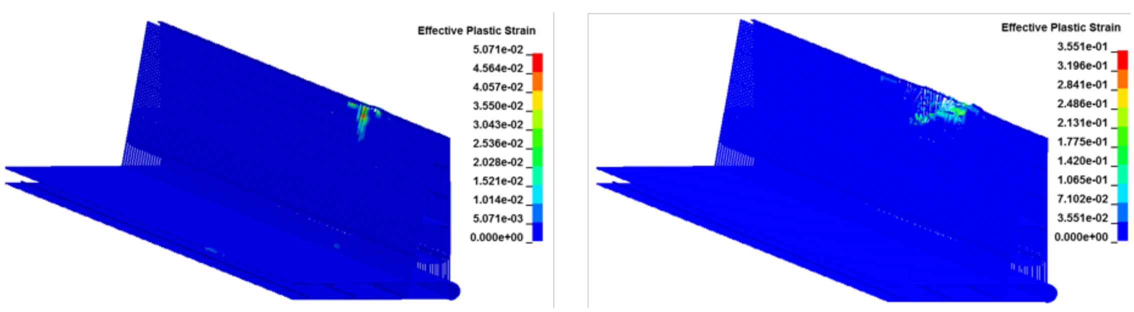


Figure 6. Steel plastic strain of Manitoba concrete bridge rail – first and fifth impact simulations – first impact (let) and fifth impact (right).

Occupant Risk Assessment

Occupant risk assessment was performed based on applicable safety evaluation criteria defined in MASH using the Test Risk Assessment Program (TRAP) for each truck impact [5,13]. The tractor-trailer models stayed upright and rollover did not occur after the simulated impact events. The impact velocities and ridedown accelerations observed in the impacts were below the MASH recommended limits [5]. The summary of results of occupant risk assessment and angular displacement for the five consecutive truck impacts into the Manitoba concrete bridge rail are shown in Table 3.

Table 3. Occupant Risk and Angular Displacement for Manitoba Concrete Bridge Rail Impact Simulation Events

Occupant Risk Parameters	Preferred/Max. Limit (MASH)	1st Impact	2nd Impact	3rd Impact	4th Impact	5th Impact
Impact Vel. [m/s (ft/s)]	9.1 (30) 12.2 (40)					
x-direction		0.37 (1.2)	0.40 (1.3)	0.4 (1.3)	0.4 (1.3)	0.43 (1.4)
y-direction		-1.58 (-5.2)	-1.55 (-5.1)	-1.55 (-5.1)	-1.58 (-5.2)	-1.52 (-5.0)
Ridedown Acc. (g's)	15 20					
x-direction		-6.4	-6.6	-6.1	-6.5	-6.5
y-direction		10.4	12.5	13.9	10.2	11.0
Angular Displacement (deg.)	**-**	**1st Impact**	**2nd Impact**	**3rd Impact**	**4th Impact**	**5th Impact**
Roll (deg.)	-	9.5	10.1	13.1	12.8	14.9
Pitch (deg.)	-	-3.2	-4.1	-1.4	4.6	5.2
Yaw (deg.)	-	15.1	14.3	12.7	13.4	13.4

The occupant models' motions during the first truck impact are illustrated for both Hybrid-III and THOR dummy models in Figure 7, which shows that the seatbelt system was able to effectively protect the occupant during the impact. The motions of occupant models during other impact events are similar to the first impact.

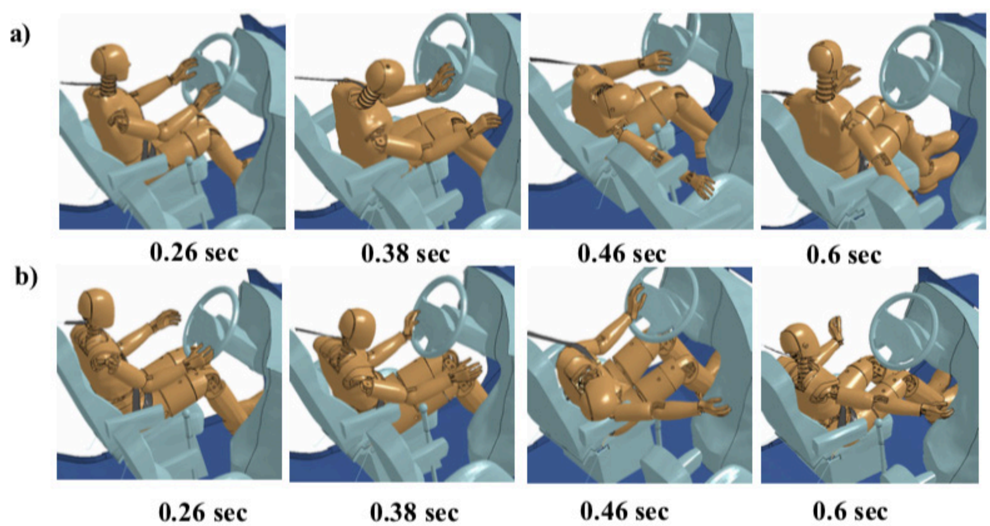


Figure 7. Motions of occupant models during 1st truck impact, a) Hybrid-III dummy model b) THOR dummy model.

The injury criteria output from first and last runs for the Manitoba concrete barrier case is shown in Table 4. The probability of head injury risk was nearly zero in the series of impacts for both the Hybrid-III dummy model and THOR dummy model. Since the simulations were performed in a side impact/sliding scenario rather than a frontal crash, the low head injury probability is predictable. The neck injury probabilities were much higher than other body parts for both runs, which made neck injury risk the main risk in these simulations. In addition, the average injury risk for the THOR dummy model was slightly higher than the average injury risk for the Hybrid-III model. The chest injury probability was the second highest among all four body sections in this study, though it was still relatively low (less than 5% of both runs for the two dummies). The methods used for obtaining the chest deflection in the two dummies were different from the user manual, and the results presented similar low injury risk. The THOR model showed lower risk compared to the Hybrid-III model. This may be related to the slightly different chest structures of the two models. The femur injury risk was one of the lowest injury risks in this study. Both runs showed low risk (less than 1%) for both the Hybrid-III and THOR model. The maximum absolute axial force occurred around 0.4 s, which is about 0.2 s after the cabin impacted the barrier.

The OIM values for the Hybrid-III and THOR models are shown in Table 5. Overall, OIM values for both dummy models were lower than 15%, which corresponds to relatively low injury risks for occupants. The predicted OIM results from both dummies were also very close, which proved the effectiveness of both dummies used in the injury assessment.

Table 4. Occupant Injury Risk Assessment for Manitoba Concrete Bridge Rail Impact Simulation Events

Occupant Model	Impact #	Head HIC-15 [-]	Neck N_{ij} [-]	Chest Chest Deflection [mm (in)]	Femur Femur Axial Force [N (lbf)]
Hybrid-III (value/injury probability)	1st Impact	81.2 0.00%	0.40 8.02%	11.40 (0.4488) 4.03%	845.37 (190.05) 0.90%
Hybrid-III (value/injury probability)	5th impact	18.9 0.00%	0.23 5.87%	7.71 (0.3035) 3.40%	684.85 (153.96) 0.85%
THOR (value/injury probability)	1st impact	135.7 0.03%	0.47 9.10%	28.52 (1.1228) 1.36%	574.18 (129.08) 0.82%
THOR (value/injury probability)	5th impact	124.1 0.02%	0.38 7.74%	17.28 (0.6803) 0.10%	510.71 (114.81) 0.81%

Table 5. OIM for Manitoba Concrete Bridge Rail Impact Simulation Events

Occupant Model	Impact #	OIM
Hybrid-III	1st Impact	12.47%
Hybrid-III	5th impact	9.84%
THOR	1st impact	11.09%
THOR	5th impact	8.60%

Finite Element (FE) Results – Concrete Median Barrier

This section discusses and compares the results of the FE simulations for the four consecutive MASH TL5 impacts into the TL5 vertical faced concrete median barrier.

Barrier Performance

The barrier was impacted consecutively at about 9,100 mm (30 ft) from the upstream end of the barrier by four tractor-trailers at an angle of 15.4 degrees and a speed of 84.9 km/h (52.7 mph). The barrier performance for each impact is summarized in Table 6 below [8]. Performance results indicated that the barrier successfully contained and redirected the impacting vehicles.

Table 6. Barrier Performance – Concrete Median Barrier [8]

	1st Truck	2nd Truck	3rd Truck	4th Truck
Maximum dynamic displacement in simulation relative to the position after pervious impact [mm (in)]	18 (0.71)	20 (0.79)	18 (0.71)	18 (0.71)
Maximum dynamic displacement in simulation from the initial position before first impact [mm (in)]	18 (0.71)	28 (1.1)	34 (1.34)	40 (1.57)
Maximum dynamic displacement in full-scale crash test [mm (in)]	38 (1.49)	NA	NA	NA
Maximum dynamic displacement time after first contact of respective vehicle to the barrier (sec)	0.77	0.74	0.74	0.82
Permanent displacement in simulation relative to the position after pervious impact [mm (in)]	8 (0.31)	8 (0.31)	6 (0.24)	10 (0.39)
Permanent displacement in simulation from the initial position before first impact [mm (in)]	8 (0.31)	16 (0.63)	22 (0.87)	32 (1.26)
Permanent displacement in full-scale crash test [mm (in)]	NA	NA	NA	NA
Was the impacting vehicle successfully contained and redirected?	Yes	Yes	Yes	Yes

Energy Values

The total energy of the system remained close to 100% during the impact period of the first through fourth tractor-trailer impacts into the barrier. The hourglass energy of the system was less than 1% for each of the impacts. The kinetic energy at the end of each simulation was in the range of 45% to 60%; this energy is due to the remaining velocity of the impacting truck.

Vehicle Stability

Figure 8 shows the frame comparison for the truck platoon impact into the concrete median barrier. Due to higher angular displacements during impact, the tractor-trailers in the second through fourth impacts took longer to stabilize compared to the first impact.

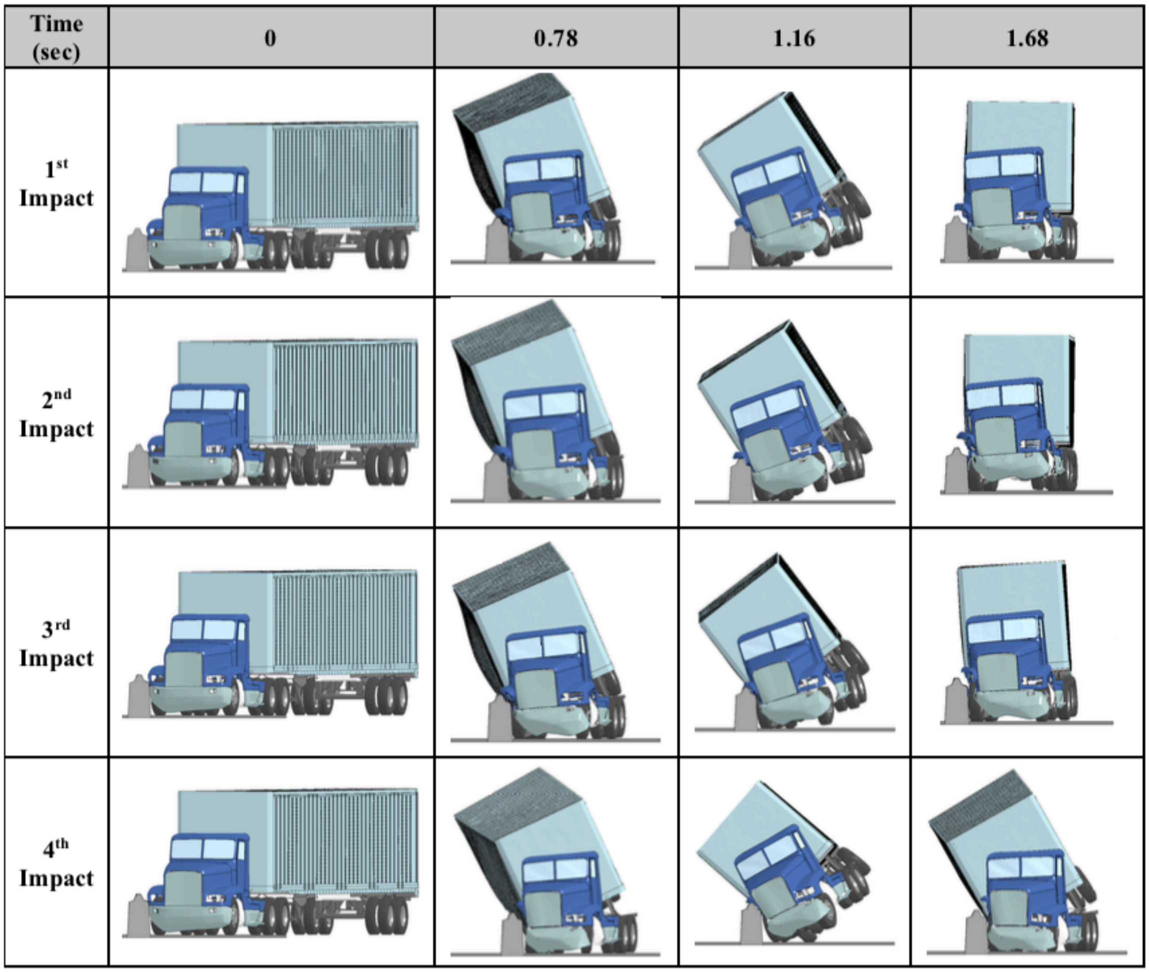


Figure 8. Frame comparison of impact simulations for concrete median barrier – front view.

Barrier Strength

Concrete erosion and steel damage at the top of the barrier due to the impacts can be observed in Figure 9. The erosion parameter was defined such that the elements were deleted when the effective plastic strain in the concrete exceeded 9.9%.

Figure 9 shows a single line of elements eroded at the top-front of the barrier protrusion, beginning at about 9,194 mm (30.2 ft) from the upstream end of the barrier and extending downstream for about 189 mm (0.62 ft). Another segment of erosion occurred at the top of the barrier protrusion beginning at about 12,500 mm (41 ft) and extending downstream for about 870 mm (2.85 ft) Almost all of the top layer of 38 mm solid elements from the front side (impact side) to the back side of the barrier protrusion was eroded at this location. Additional damage occurred at the front-edge of the barrier (below protrusion) beginning at 27,121 mm (89 ft) from the upstream end and stretching 1,062 mm (3.5 ft) downstream.

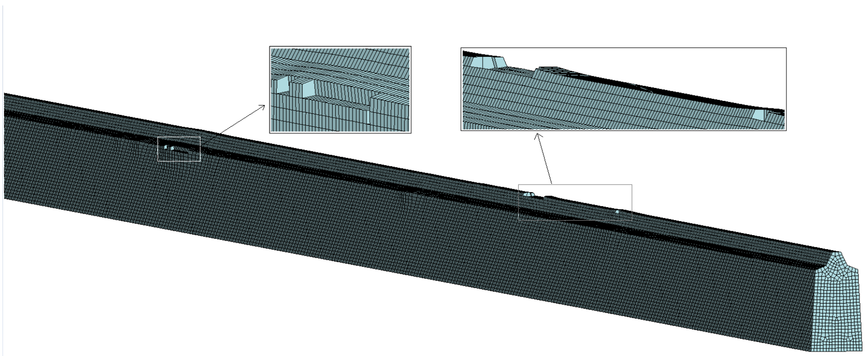


Figure 9. Erosion of concrete median barrier – first impact computer simulation.

Figure 10 shows the first eroded segment on the top protrusion grew after the fourth impact, now beginning about 8,396 mm (27.5 ft) from the upstream end, and extending to merge into the second eroded segment. A V-shaped erosion on the front face extended down and reached the fifth layer of elements from the bottom of the barrier. The second eroded segment, now a continuation of the first segment, also grew—mostly on the top protrusion—and transitioned to a single layer of front edge elements. The eroded segment stopped at 23,018 mm (75.5 ft) from the upstream end. After the fourth impact, the furthest front edge damage stretched 7,557 mm (24.8 ft), beginning at 26,550 mm (87.1 ft) from the upstream end and progressing upward towards the crown of the protrusion.

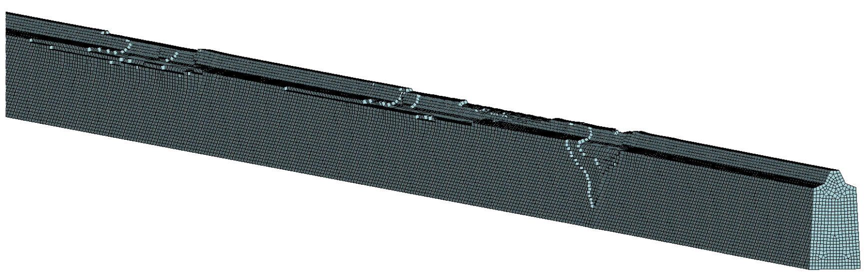


Figure 10. Erosion of concrete median barrier – fourth impact computer simulation.

Figure 11 shows the plastic strains in the steel reinforcement of the barrier at the end of each impact for four consecutive tractor-trailer impacts. The steel reinforcement, modeled as beam elements, was not considered in the calculations if the maximum plastic strain exceeded 20%. Reinforcement in navy blue represents negligible or no plastic strain. At the end of the first and fourth impact, maximum steel plastic strain of 1.7% and 3.5% were observed, respectively; the damage was in a small region at the top of the barrier.

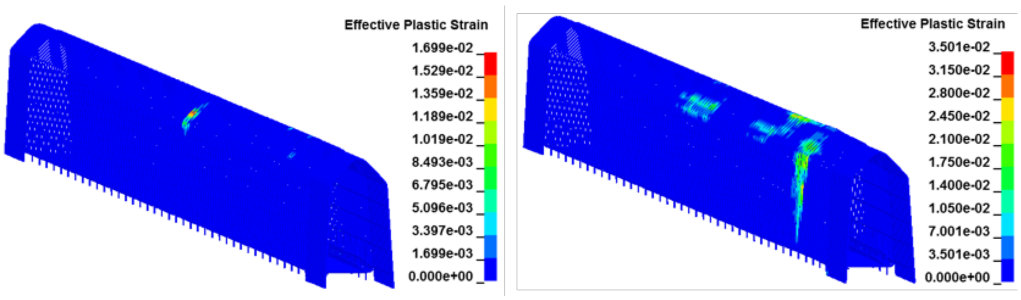


Figure 11. Steel plastic strain of concrete median barrier results for four consecutive impact computer simulations (right: first impact; left: fourth impact).

Occupant Risk Assessment

Occupant risk assessment was performed based on applicable safety evaluation criteria defined in MASH using the TRAP program for each truck impact [5, 13]. The tractor-trailer models stayed upright and rollover did not occur after the simulated impact events. The impact velocities and ridedown accelerations observed in the impacts were below the MASH recommended limits [5]. The summary of results of occupant risk assessment for the four consecutive truck impacts into the concrete median barrier are shown in Table 7.

Table 7. Occupant Risk and Angular Displacement for Concrete Median Barrier Impact Simulation Events

Occupant Risk Parameters	Preferred/Max. Limit (MASH)	1st Impact	2nd Impact	3rd Impact	4th Impact
Impact Vel. [m/s (ft/s)] **x-direction** **y-direction**	9.1 (30) 12.2 (40)	 0.58 (1.9) -1.80 (-5.9)	 0.61 (2.0) -1.80 (-5.9)	 0.64 (2.1) -1.86 (-6.1)	 0.70 (2.3) -1.74 (-5.7)
Ridedown Acc. (g's) **x-direction** **y-direction**	15 20	 -9.7 8.1	 7.5 9.6	 -7.5 11.2	 -7.9 -8.1
Angular Displacement (deg.)	-	**1st Impact**	**2nd Impact**	**3rd Impact**	**4th Impact**
Roll (deg.)	-	19.7	19.8	19.7	31.2
Pitch (deg.)	-	6.4	7.1	6.1	10.3
Yaw (deg.))	-	12.8	12.3	12.8	9.9

The injury criteria recorded during the first and the last (4th) tractor-to-barrier impact simulations are provided in Table 8. The results show similar effectiveness to the Manitoba concrete barrier cases. The risks of head injury for all cases were less than 0.1%. The probability of neck injuries had the highest values among the four different body sections, but values were still less than 4%. In addition, the chest and femur injury probabilities were higher than the head risks, but were still relatively low (below 5%).

The OIM values recorded during impact simulations with the Hybrid-III and THOR models are shown in Table 9. The low OIM values for both dummies recorded in all simulations indicates that occupants' injury risks are very low during truck-to-barrier impacts that result from errant truck platoons.

Table 8. Occupant Injury Risk Assessment for Concrete Median Barrier Impact Simulation Events

Occupant Model	Impact #	Head HIC-15 [-]	Neck N_{ij} [-]	Chest Chest Deflection [mm (in)]	Femur Femur Axial Force [N (lbf)]
Hybrid-III (value/injury probability)	1st Impact	44.5 0.00%	0.36 7.50%	10.20 (0.4016) 3.81%	1069.87 (240.52) 0.97%
Hybrid-III (value/injury probability)	4th impact	33.6 0.00%	0.37 7.60%	14.45 (0.5688) 4.63%	941.71 (211.70) 0.93%
THOR (value/injury probability)	1st impact	110.9 0.01%	0.35 7.32%	26.66 (1.0496) 0.97%	474.62 (106.70) 0.80%
THOR (value/injury probability)	4th impact	68.21 0.00%	0.40 8.02%	26.31 (1.0358) 0.90%	530.36 (119.23) 0.81%

Table 9. Occupant Injury Measurement for Concrete Median Barrier Impact Simulation Events

Occupant Model	Impact #	Occupant Injury Measure
Hybrid-III	1st Impact	11.89%
Hybrid-III	4th impact	10.88%
THOR	1st impact	8.95%
THOR	4th impact	9.59%

The occupant body injury values were also compared to the injury assessment reference values (IARVs). The IARVs represent the borders between acceptable and marginal ratings for a given injury parameter recorded during a crash test, as shown in Table 10. Acceptable ratings are ratings corresponding to measures below the IARVs. The maximum values of injury criteria recorded during the crash simulation were well below the IARVs, which suggested very low injury risk for tractor trailer drivers. For example, three injury values (Head Injury Criterion [HIC], chest deflection and femur axial forces) were less than 20% of IARVs.

Table 10. IARVs for Injury Parameters During Crash Tests

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

Seat Position Parameter Sensitivity Study

According to recent developments in automated trucks, the driver cabin will become more like an office, so the driver's seat of these trucks can be better adjusted for office work. In this section, potential errant platoon accident injury risks are evaluated for an occupant positioned in a different pre-crash posture than in current trucks; currently, drivers are seated immediately in front of the steering wheel.

Seat Position Parameter Setup

Based on recent automated driving seat setups proposed in literature, four different seat rotation angles of 15°, 30°, 45° and 60° relative to a traditional seat were used. These angles may not cover all possible circumstances, but might provide a rough estimation about consequence of driver seat rotation. The same crash pulses corresponding to a truck impacting a Manitoba concrete bridge rail were used. As shown in Figure 12, the seat was moved toward the left back corner of the cabin, which was necessary to avoid occupant model overlapping with the cabin interiors.

Seat Position Parameter Sensitivity Observation

The results of the simulations with rotated seated were initially qualitatively analyzed by observing the occupants' overall kinematics during the impacts. The interaction of the occupant FE model with the restraint system at about 0.18 s after the beginning of impact are illustrated in Figure 13, which shows that in the case of a seat rotation angle of 15°, the shoulder belt slid along the arm of the dummy and it couldn't adequately protect the upper body during the crash. Relatively better interactions with the shoulder belt were observed for rotation angles from 30° to 60°, though these may have been caused by the Hybrid-III dummy's simplified shoulder.

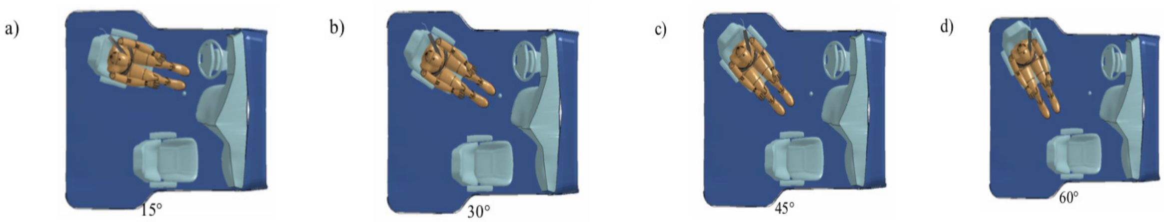


Figure 12. Position Parameter Sensitivity Study Setup
a) 15° b) 30° c) 45° d) 60°

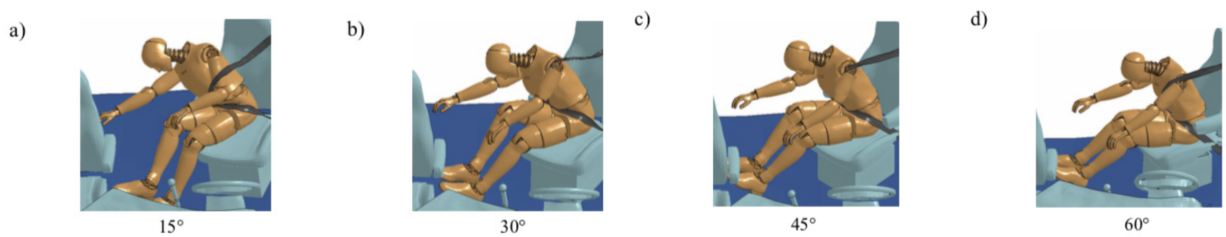


Figure 13. Occupant dummy model position at 0.45 s.
a) 15° b) 30° c) 45° d) 60°

The dummy's interaction with the belt during in the 15° rotation seat angle case is illustrated in Figure 14, which shows that the occupant slips through the shoulder lap, so a regular 3-point seatbelt system will not provide protection during a crash. If an actual human driver were holding something like a tablet computer during a similar impact, unexpected consequences might be expected to occur.

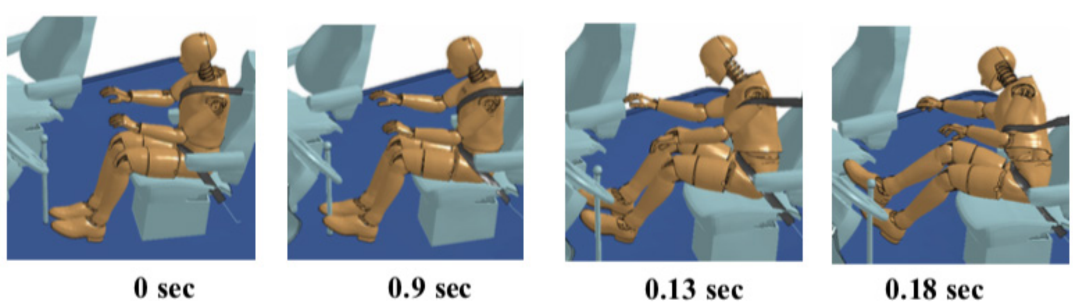


Figure 14. Motions of occupant model with seat rotation angle of 15°.

The values of injury criteria recorded for rotated seat cases are provided and compared with the nominal position (the 0° case) in Table 11. The HIC-15 values ranged from 20 up to 81, which corresponds to a very safe region. The highest HIC-15 value was in nominal posture, where the shoulder belt fully restrained the chest, and the head may experience a more aggressive change of acceleration. However, even in this position, the risk of injury was very low (< 0.01%). The risk of neck injuries, assessed with Nij criteria, showed higher values than other body region criteria. The maximum values were recorded in the nominal posture and 60° case, with probabilities of injuries under 8%. The chest injury probability is higher for the rotated cases as a result of the shoulder belt's weak performance, which allowed significant motion of the dummy's upper body.

It should be also noted that the poor performance of the shoulder belt in rotated cases resulted in high forces in the lapbelt and an increased risk of abdominal injuries, which could not be recorded with the Hybrid-III dummy's current instrumentation. In terms of the lower extremity injury risks, as found in the chest case, slightly higher femur force values were observed in the rotated cases than in the nominal case. Overall, the OIM values were relatively lower in all cases, as shown in Table 12, suggesting a low probability of injury for occupants in nominal and rotated postures.

Table 11. Occupant Injury Risk Assessment for Rotated Seat Cases

Angle of Rotation	Head HIC-15 [-]	Neck N_{ij} [-]	Chest Chest Deflection [mm (in)]	Femur Femur Axial Force [N (lbf)]
0° (value/injury probability)	81.2 0.00%	0.40 8.02%	11.40 (0.4488) 4.03%	845.4 (190.05) 0.90%
15° (value/injury probability)	16.2 0.00%	0.24 5.98%	17.96 (0.7071) 5.42%	1398.1 (314.31) 1.07%
30° (value/injury probability)	19.7 0.00%	0.26 6.21%	15.56 (0.6126) 4.86%	1113.7 (250.37) 0.98%
45° (value/injury probability)	16.2 0.00%	0.23 5.87%	18.28 (0.7197) 5.50%	935.0 (210.2) 0.92%
60° (value/injury probability)	29.1 0.00%	0.37 7.60%	19.75 (0.7776) 5.87%	1429.8 (321.43) 1.08%

Table 12. Occupant Injury Measurement for Rotated Seat Cases

Angle of Rotation	OIM
0°	12.47%
15°	12.03%
30°	11.64%
45°	11.87%
60°	13.96%

Overall, even considering a rotating seat relative to the truck, the occupant injury risk remained low during the truck-barrier impacts investigated in this study. However, results did reveal a limited effectiveness of the traditional 3-point belt system, which reduced chest and abdomen protection. Therefore, careful consideration is recommended when rotatable driver seats are implemented in self-driving trucks.

Discussion

Under MASH TL5 conditions, detailed FEA models of the Manitoba concrete bridge rail and the concrete median barrier were impacted by five and four tractor-van trailer models, respectively. These simulations were analyzed to assess infrastructural adequacy and vehicle stability in the event of errant truck platoons. Under the impacts at the given conditions, final permanent deflections of the Manitoba concrete bridge rail and the concrete median barrier were 75 mm (2.95 in) and 32 mm (1.26 in) respectively. Erosion of the solid elements in the Manitoba concrete bridge rail deck, representing deck concrete failure, did not occur, though strain values close to maximum effective plastic strain of 9.45% were observed in the longitudinal direction near the point of impact. Cracks are likely to occur in this highly strained region of the deck during full-scale impact tests. The impacting tractor-van trailers maintained stability during the simulated impact events, and the barrier FEA models were able to contain and redirect the impacting vehicles. The simulation results suggest that catastrophic failure is unlikely under any of the in-series impacts into barriers conditions selected for this study. In addition, low injury risks were predicted during the truck-to-barrier impacts for the occupants of the first and the last trucks. The OIMs for all cases were lower than 15%, which suggests very low injury risks for vehicle occupants. The barrier design can be considered effective in protecting belted vehicle occupants in platoons.

Conclusions and Recommendations

The analysis results suggest that the Manitoba concrete bridge rail and the concrete median barrier are potentially capable of containing and redirecting multiple tractor trailer impacts at MASH TL5 impact conditions. It can be assumed that other concrete barriers with similar design capacity will show similar results. Taller barriers are likely to perform better than shorter barriers against errant truck platoons. The barrier design could be considered effective in protecting the occupants of vehicles equipped with the current 3-point seatbelt system, but may not be considered as effective when rotated seat design is used.

Researchers highly recommend additional studies to identify the possible impact conditions for following truck impacts resulting from errant truck platoons. Though the first impact for each system was validated against the respective full-scale crash test, there were no data to validate the following impact simulations. Researchers recommend conducting multiple impact tests in order to validate the simulation results of following impacts. This will allow researchers to make more definite conclusions before fully considering the barrier systems sufficient for multiple impacts at MASH TL5 conditions. In addition, considering that departments of transportation in different states have different standards for minimum bridge deck depth, researchers suggest additional studies to examine and verify the adequacy of deck capacity when deck depth varies.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the project page of the Safe-D website. The final project dataset is located in the Safe-D Collection of the VTTI Dataverse.

Education and Workforce Development Products

The EWD products developed as a part of this project are listed below.

- In October 2018, a TTI graduate student involved in the project successfully defended a graduate thesis based on the subjects developed within the research project. Some contents of this research report are published as part of the thesis: Sharma, R., Finite Element Analysis of Truck Platoon Impact into Roadside Safety Barriers, Master's Thesis, Texas A&M University, College Station, 2018.

- A presentation about the results of this research and the importance of using a seatbelt was given at West Salem Elementary School STEM Night (Salem, Virginia), March 27, 2018.

Technology Transfer Products

The T2 products developed as a part of this project are listed below.

- Researchers have submitted or have prepared the submission of papers to Elsevier, International Journal of Vehicle Systems Modelling and Testing (Interscience Publishers) and other publications. These publications are listed on the project page of the Safe-D website.
- A presentation related to the results obtained in this project was provided during the International Research Council on the Biomechanics of Injury (12–14 September 2018, Athens Greece) by Dr. C. Untaroiu.
- Researchers are preparing a webinar presentation based on the results of the research; this will be available on the project page of the Safe-D website upon completion.

Data Products

The data products uploaded to the Safe-D collection on the VTTI Dataverse as a part of this project are available at https://doi.org/10.15787/VTT1/D9UA9N and listed below.

- From full-scale tractor-van trailer simulations:
  - Nodal time history data for cabin only motion simulation.
  - Accelerometer and gyrometer data extracted from cabin and rear-axle accelerometers.
  - GLSTAT energy data.
  - Roll, pitch and heave comparison graphs.
  - Videos for impact simulations.
  - Time history data of injury risk evaluation variable related to head, neck, chest and femur.
  - Graphs of injury risk evaluation variable plots.
  - Ls-dyna .k files used to generate injury risk evaluation simulations.
  - Ls-dyna d3plot files for injury risk evaluation simulation results.

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Appendices

Appendix A

Manitoba Concrete Bridge Rail

System Description

The Manitoba concrete 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 concrete bridge rail and deck [7]. The 45.72 m (150 ft) long test installation was designed as two segments – upstream and downstream, with a 168 mm gap between the segments, in order to simulate a joint in the concrete bridge rail and deck. Steel end caps were casted into the ends of the concrete 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 full-scale crash test (MAN-1) was performed with the tractor-van trailer impacting just upstream from the simulated joint in the concrete bridge rail. To make sure that the interior section of the barrier could also withstand the impact, for the full-scale crash test, traverse rebar spacing in the barrier end section was modified such that the end section had same capacity as the interior section i.e. 874 kN (196 kips) [7].

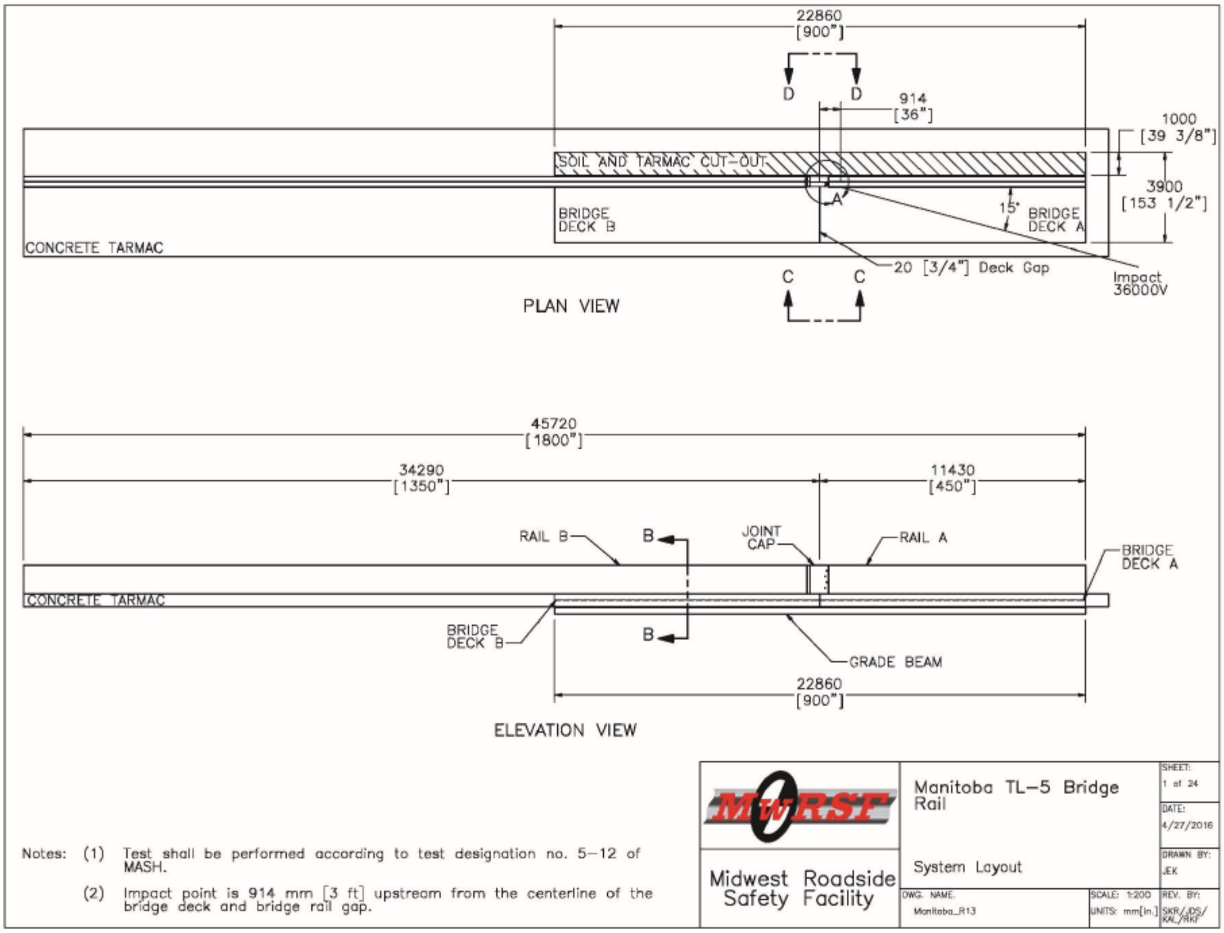


Figure 15. Test installation layout, Test No. MAN-1 [7].

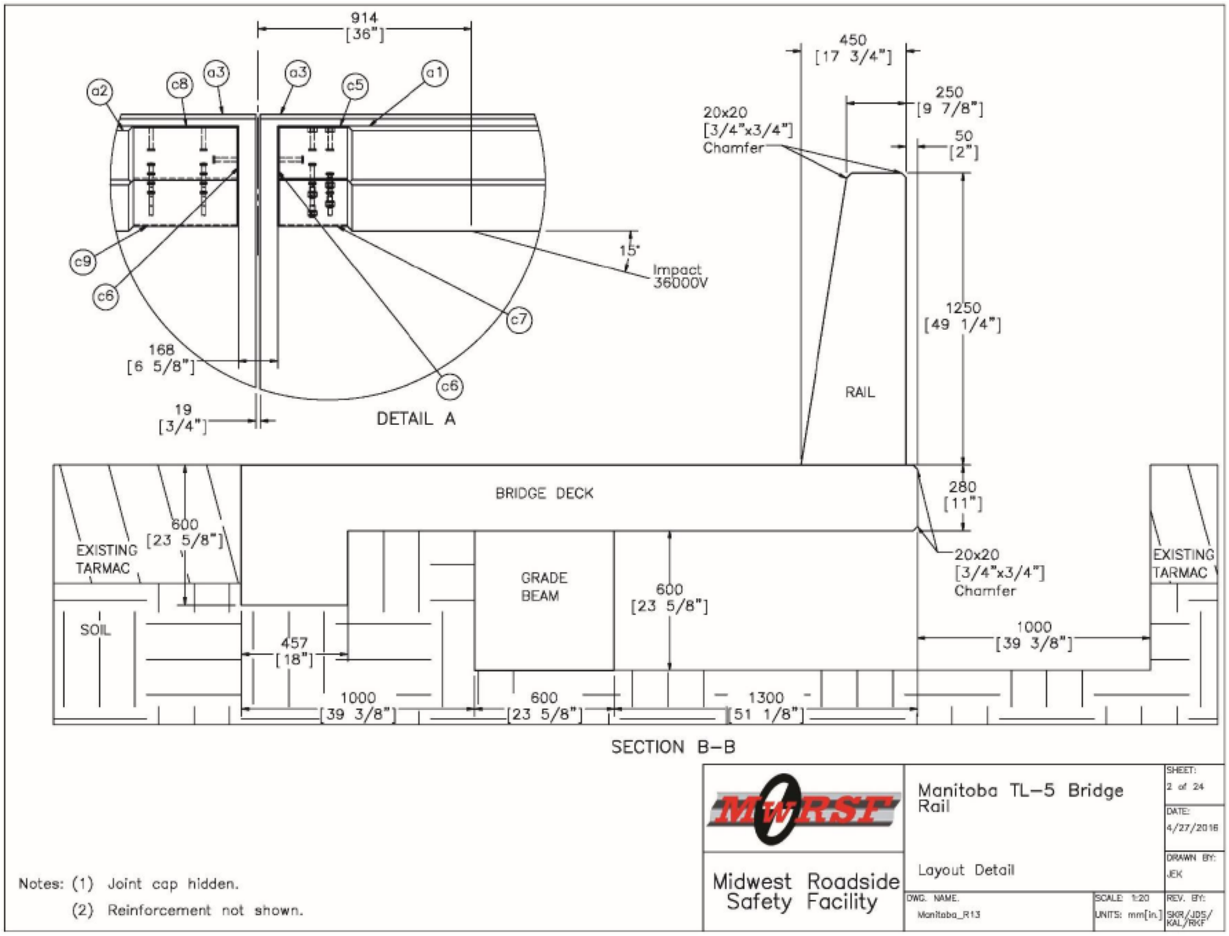


Figure 16. Layout detail, Test No. MAN-1 [7].

The Manitoba concrete bridge rail was modeled in LS-Dyna as a single 45.72 m (150 ft) long barrier segment to simulate the full-scale crash test. The FEA model tested the capacity of the interior section of the rail segment as opposed to the full-scale crash test that tested the end section of the barrier [6]. 50 mm x 50 mm (2 in x 2 in) constant stress solid brick elements 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 [6]. 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. Failure strain of 20% was set for the rebar so that the beam element is deleted from calculation after the plastic strain reaches this value. Constrained_Beam_In_Solid (CBIS) card was used to constrain the reinforcing steel in concrete [6]. MAT_CSCM_Concrete (MAT_159) was used to model the concrete [6]. The compressive strength of 45 MPa (6,500 psi) and default material parameter options were used to define the material card for the concrete model. The concrete model was allowed to erode during the impact and MAT_Add_Erosion card was used to define the concrete erosion parameters [6]. After running multiple simulations with various parameters, 9.45% effective plastic strain criterion was observed to develop concrete erosion comparable to the full-scale crash test.

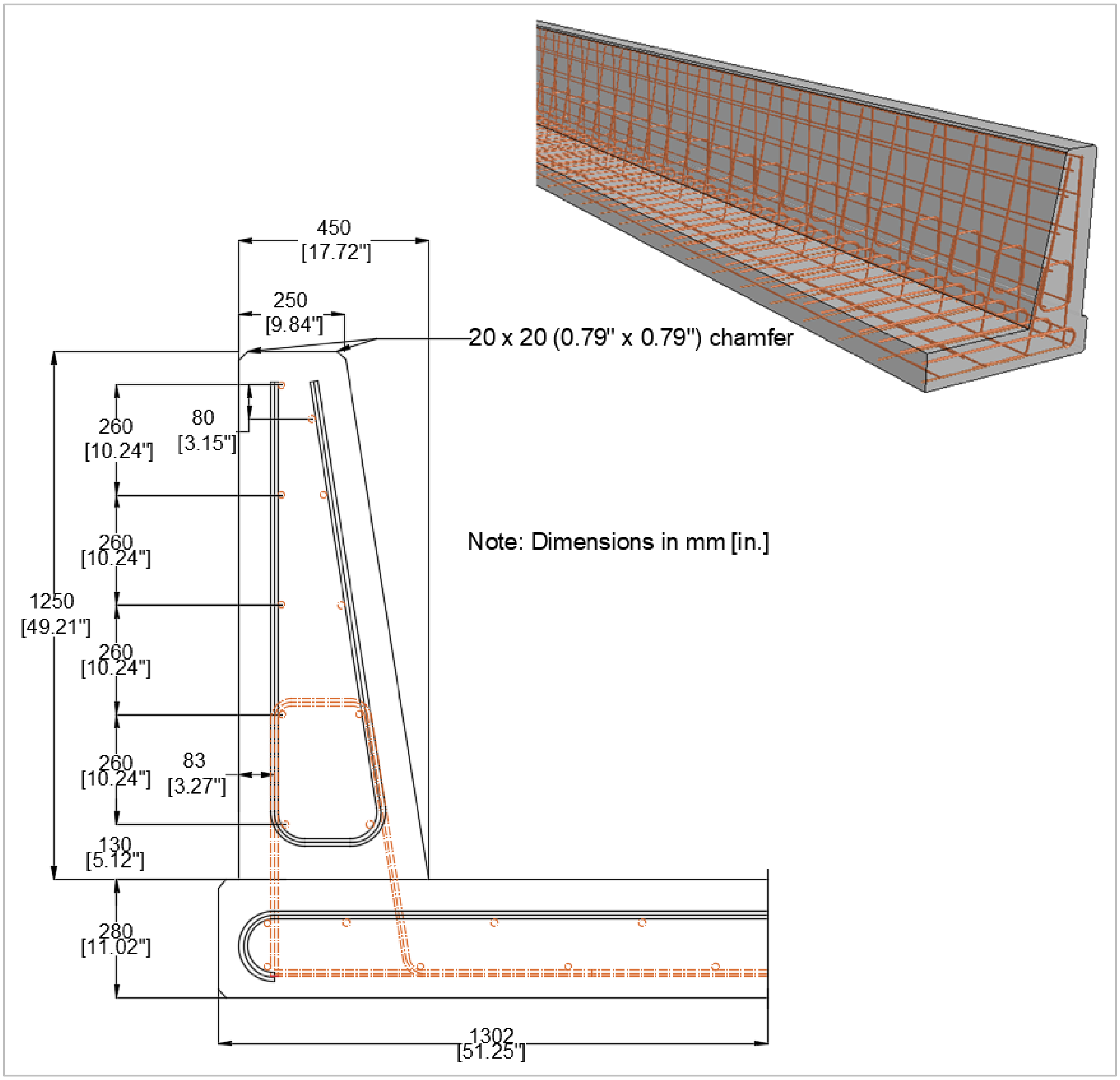


Figure 17. Cross-section and layout of Manitoba concrete bridge rail FEA model.

A 2004 International 9200 tractor with a 2001 Wabash National 16 m (53 ft) trailer was used as the test vehicle for Manitoba concrete bridge rail test [7]. An existing proprietary tractor-van trailer FEA model was used by TTI in the impact simulations. The FEA model was initially developed by National Crash Analysis Center (NCAC) and released by National Transportation Research Center, Inc. (NTRCI) [14,15,16]. A number of 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 coefficient between the truck tires and the barrier was set to 0.45, the friction coefficient between the truck body and the barrier was set to 0.2 and the friction coefficient between the truck tires and ground was set to 0.85. Contact_Eroding_Nodes_To_Surface, Contact_Eroding_Surface_To_Surface and Contact_Automatic_Nodes_To_Surface cards were used to define contact between truck beams to concrete, truck body to concrete and truck body to reinforcement respectively [6].

Validation

VALIDATION/VERIFICATION REPORT
FOR

A ________________<u>MASH08 Tractor-Trailer</u>________________________________
(Report 350 or MASH08 or EN1317 Vehicle Type)

Striking a __________<u>Manitoba Constrained Width, Tall Wall, Bridge Rail</u>__________
(roadside hardware type and name)

Report Date: _______<u>02-19-2018</u>____

Type of Report (check one)

☐ Verification (known numerical solution compared to new numerical solution) or
☒ Validation (full-scale crash test compared to a numerical solution).

General Information	Known Solution	Analysis Solution
Performing Organization	MWRsF	TTI
Test/Run Number:	MAN-1	TTI_MAN-1_RUN-1
Vehicle:	2004 International 9200 Tractor, 2001 Wabash National Trailer	Tractor Version 2010-03-02 and Trailer Model Version 10-0304
Impact Conditions		
Vehicle Mass:	36,322 kg (80,076 lb)	36,170 kg (79,741)
Speed:	83.2 km/h (51.7 mph)	83.2 km/h (51.7 mph)
Angle:	15.2 deg.	15.2 deg
Impact Point:	0.46 m (1.5 ft) upstream from open joint	10.96 m (36.0 ft) downstream from the upstream end of the barrier

PART I: BASIC INFORMATION

These forms may be used for validation or verification of roadside hardware crash tests. If the known solution is a full-scale crash test (i.e., physical experiment) then the procedure is a <u>validation</u> exercise. If the known solution is a numerical solution (e.g., a prior finite element model using a different program or earlier version of the software) then the procedure is a <u>verification</u> exercise.

Provide the following basic information for the validation/verification comparison:

1. What type of roadside hardware is being evaluated (check one)?
   ☒ Longitudinal barrier or transition
   ☐ Terminal or crash cushion

☐ Breakaway support or work zone traffic control device
☐ Truck-mounted attenuator
☐ Other hardware: ____

2. What test guidelines were used to perform the full-scale crash test (check one)?
   ☐ NCHRP Report 350
   ☒ MASH08 (16)
   ☐ EN1317
   ☐ Other: ____

3. Indicate the test level and number being evaluated (fill in the blank). ________5-12______

4. Indicate the vehicle type appropriate for the test level and number indicated in item 3 according to the testing guidelines indicated in item 2.

NCHRP Report 350/MASH08

☐ 700C ☐ 820C ☐ 1100C
☐ 2000P ☐ 2270P
☐ 8000S ☐ 10000S
☒ 36000V
☐ 36000T

EN1317

☐ Car (900 kg) ☐ Car (1300 kg) ☐ Car (1500 kg)
☐ Rigid HGV (10 ton) ☐ Rigid HGV (16 ton) ☐ Rigid HGV (30 ton)
☐ Bus (13 ton)
☐ Articulated HGV (38 ton)

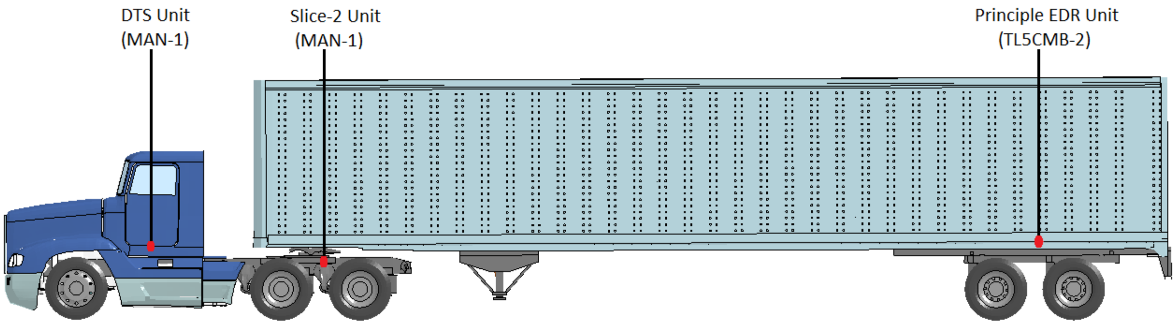


Figure 18. Accelerometer locations in tractor-van trailer FEA model.

Table 13. Analysis Solution Verification Table – Manitoba Concrete Bridge Rail

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	4.8	YES
Hourglass Energy of the analysis solution at the end of the run is less than five percent of the total initial energy at the beginning of the run.	0.15	YES
Hourglass Energy of the analysis solution at the end of the run is less than ten percent of the total internal energy at the end of the run.	2.9	YES
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run.	22.5	**NO***
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0.1	YES
The part/material with the most mass added had less than 10 percent of its initial mass added.	4.6	YES
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	4.6	YES
There are no shooting nodes in the solution?	Yes	YES
There are no solid elements with negative volumes?	Yes	YES

**The hourglass energy to total internal energy ratio of the concrete was 22.5% which is larger than the suggested value. It was assumed that the numerical erosion of the concrete had some effect on the hourglass behavior. The response of the barrier was very similar to the full-scale crash test other than the local permanent deflection. The global energy of the system was stable and the hourglass effect decreased to a value very close to or below 10% for the following truck impacts.*

Roadside Safety Verification and Validation Program (RSVVP) was used for the purpose of quantitative validation of the numerical model [9, 10]. The full-scale crash test data from DTS and SLICE2 accelerometer and rate sensor units was provided by MwRSF. DTS unit was located in the cab of the tractor while SLICE2 unit was mounted inside the trailer directly above front tandem axle [7]. Acceleration and angular displacement data were compared between the test and simulation according to Sprague and Geers (S&G) metrics and variance (ANOVA) metrics. The data from the simulation was filtered in LS-Dyna using SAE 180 filter. The evaluation was performed over a period of 1.25 s of impact event. The acceptance criteria are maximum value of 40 for S&G metrics, 35% for ANOVA standard deviation and 5% for ANOVA mean [9, 10]. Summary of quantitative multi-channel time history comparison of MAN-1 test data and FEA are shown in Table 14 and Table 15.

Table 14. Quantitative Multi-Channel Time History Comparison of Test vs FEA – DTS Unit

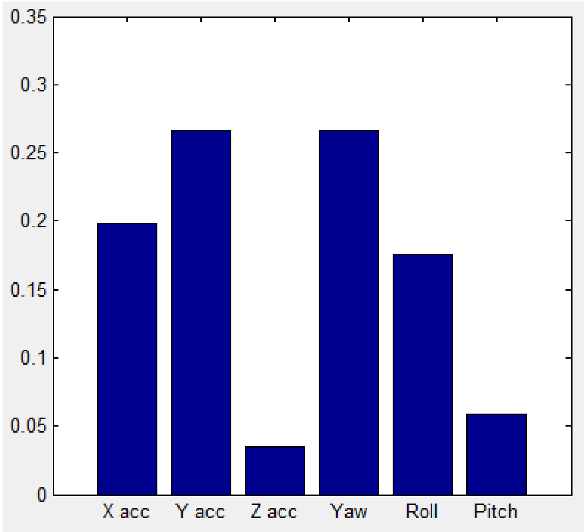
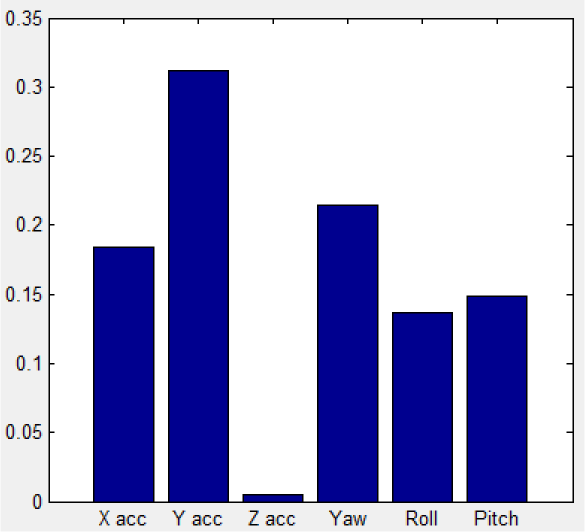
<table>
<tr><th colspan="5">Evaluation Criteria (time interval [0 sec; 1.25 sec])</th></tr>
<tr><td colspan="5">Channels (Select which was used)</td></tr>
<tr><td colspan="2">☒ X Acceleration</td><td>☒ Y Acceleration</td><td colspan="2">☒ Z Acceleration</td></tr>
<tr><td colspan="2">☒ Roll rate</td><td>☒ Pitch rate</td><td colspan="2">☒ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weighting Method</td><td>☐ Peaks
☐ Area I
☒ Area II
☐ Inertial</td><td colspan="2">Channel Weight Factors
</td></tr>
<tr><td rowspan="2">O</td><td rowspan="2">Sprauge-Geer Metrics
Values less or equal to 40 are acceptable.</td><td></td><td>M</td><td>P</td></tr>
<tr><td></td><td>84.9*</td><td>32</td></tr>
<tr><td rowspan="2">P</td><td rowspan="2">ANOVA Metrics
Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$)
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td></td><td>Mean Residual</td><td>Standard Deviation of Residuals</td></tr>
<tr><td></td><td>-2.5</td><td>32.3</td></tr>
</table>

Table 15. Quantitative Multi-Channel Time History Comparison of Test vs FEA – SLICE2 Unit

Evaluation Criteria (time interval [0 sec; 1.25 sec])			
Channels (Select which was used)			
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**	
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**	
Multi-Channel Weighting Method	☐ **Peaks** ☐ **Area I** ☒ **Area II** ☐ **Inertial**	**Channel Weight Factors** 	
O	***Sprauge-Geer Metrics*** Values less or equal to 40 are acceptable.	**M** **65***	**P** **41.1***
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)	**Mean Residual** **-14.8***	**Standard Deviation of Residuals** 27.7

** According to the results, the FEA model was only in marginal agreement with the full-scale crash test. As the acceptance criteria is developed from results of multiple tests involving a car, these criteria can be considered to be strict for the tractor-van trailer impact event which is a longer multi-body impact compared to a car impact. So, the Sprague-Geer results were considered to be on the borderline for this assessment. It was noted that similar approach was followed on some previous studies for validation of a tractor-van trailer. It was assumed that the differences in the tractor-van trailers between the full-scale crash test and simulation event had an effect on the poor agreement in acceleration behavior.*

Table 16. Evaluation Criteria Test Applicability Table – Manitoba Concrete Bridge Rail

<table>
<tr><th>Evaluation Factors</th><th colspan="2">Evaluation Criteria</th><th>Applicable Tests</th></tr>
<tr><td rowspan="2">Structural Adequacy</td><td>A</td><td>Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38</td></tr>
<tr><td>B</td><td>The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>60, 61, 70, 71, 80, 81</td></tr>
<tr><td></td><td>C</td><td>Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>30, 31,, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53</td></tr>
<tr><td rowspan="7">Occupant Risk</td><td>D</td><td>Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>All</td></tr>
<tr><td>E</td><td>Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle. (Answer Yes or No)</td><td>70, 71</td></tr>
<tr><td>F</td><td>The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>All except those listed in criterion G</td></tr>
<tr><td>G</td><td>It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>12, 22 (for test level 1 – 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44)</td></tr>
<tr><td rowspan="2">H</td><td>Occupant impact velocities should satisfy the following:
<table>
<tr><th colspan="3">Occupant Impact Velocity Limits (ft/s)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal and Lateral</td><td>30 (9.1)</td><td>40 (12.2)</td></tr>
</table></td><td>10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81</td></tr>
<tr><td><table><tr><td>Longitudinal</td><td>10 (3.0)</td><td>15 (4.9)</td></tr></table></td><td>60, 61, 70, 71</td></tr>
<tr><td>I</td><td>Occupant ridedown accelerations should satisfy the following:
<table>
<tr><th colspan="3">Occupant Ridedown Acceleration Limits (g's)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr>
</table></td><td>10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td rowspan="3">Vehicle Trajectory</td><td>L</td><td>The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec (12.2 m/sec) and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.</td><td>11,21, 35, 37, 38, 39</td></tr>
<tr><td>M</td><td>The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39</td></tr>
<tr><td>N</td><td>Vehicle trajectory behind the test article is acceptable.</td><td>30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81</td></tr>
</table>

Table 17. Roadside Safety Phenomena Importance Ranking Table – Manitoba Concrete Bridge Rail

Evaluation Criteria				Known Result	Analysis Result	Relative Diff. (%)	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		Yes
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	52 mm (2.05 in)	50 mm (1.97 in)	4%	Yes
		A3	The relative difference in the length of vehicle-barrier contact is less than 20 percent.				
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	NA	NA	NA	NA
		A5	The rail element did not rupture or fail (Answer Yes or No)	NA	NA		NA
		A6	There were no failures of connector elements (Answer Yes or No).	NA	NA		NA
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	No	No		Yes
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	No	No		Yes

Table 17. Roadside Safety Phenomena Importance Ranking Table (continued)

Evaluation Criteria				Known Result	Analysis Result	Relative Diff.	Agree?
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Yes or No)	Pass	Pass		Yes
Occupant Risk	G	G1	It is preferable, although not essential, that the vehicle remain upright during and after collision. (Answer Yes or No)	Pass	Pass		Yes
Occupant Risk	G	G2	The relative difference in the maximum vehicle roll angle is less than 20 percent.	16.4	9.5	42%	**No***
Occupant Risk	G	G3	The relative difference between the maximum rotation between the tractor and trailer is less than 20 percent (Tests 5-12, 6-12, 5-22 and 6-22 only			NA	NA
Occupant Risk	G	G4	The vehicle ballast or load significantly shifted during the collision (Tests 12 and 22 only)	No	No		Yes
Occupant Risk	G	G5	The frontal axle connection failed (Tests 12 and 22 only).				
Occupant Risk	H	H1	The relative difference in the Occupant impact velocity is less than 20 percent or < 2m/s (6.56 ft/s): • Longitudinal OIV [m/s (ft/s)]	-0.71 (-2.33)	1.2 (3.94)	< 2 (6.56)	Yes
Occupant Risk	H	H1	• Lateral OIV [m/s (ft/s)]	-4.92 (-16.14)	5.2 (17.06)	Abs. Value < 2 (6.56)	Yes
Occupant Risk	H	H2	• THIV (m/s)	4.41 (14.47)	5.3 (17.39)	< 2 (6.56)	Yes
Occupant Risk	I		The relative difference in the Occupant Ridedown Accelerations is less than 20 percent or < 4g: • Longitudinal ORA	-4.04	-6.4	< 4g	Yes
Occupant Risk	I		• Lateral ORA	-6.3	-10.4	~ < 4g	**Border-line****
Occupant Risk	I		• PHD	6.52	10.5	< 4g	Yes
Occupant Risk	I		• ASI (DTS Unit)	0.67	0.73	9%	Yes

**The maximum vehicle roll magnitude from the simulation was only in marginal agreement with the full-scale crash test, however the Sprague-Geer metrics were in reasonable agreement with -43.5% and 28.5% for magnitude and phase respectively.*

*** The Lateral ORA was considered borderline as the difference in known and analysis result was 4.1*g which is very close to 4*g.*

Table 17. Roadside Safety Phenomena Importance Ranking Table (continued)

Evaluation Criteria				Known Result	Analysis Result	Relative Diff. (%)	Agree?
	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	Yes	Yes	NA	Yes
		M2	The relative difference in the exit angle at loss of contact is less than 20 percent.	0	0	0	Yes
		M3	The relative difference in the exit velocity at loss of contact is less than 20 percent.	61.6 km/h (38.3 mph)	67.7 km/h (42.1 mph)	9.9%	Yes
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	No	No		Yes
		M5	One or more tires separated from the vehicle (Answer Yes or No).	No	No		Yes

The sequential snapshots from the full-scale crash test were compared to the FEA analysis as a part of qualitative evaluation of the model validity. Table 20 and Table 21 show the frame comparison from test no. MAN-1 and computer simulation starting at zero second, i.e. the time of first contact between tractor-trailer and the barrier during impact event. The kinematic response of the FEA vehicle was in good agreement with the full-scale crash test vehicle and the phenomenological events from the full-scale crash test were well replicated by the FEA. The results of the quantitative validation were only in marginal agreement with the default requirements. However, the tractor-van trailer was deemed applicable for TL5 simulations based on overall quantitative and qualitative evaluation.

Table 18. Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Front View

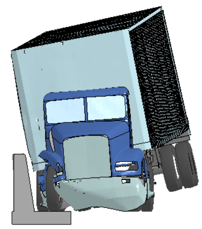
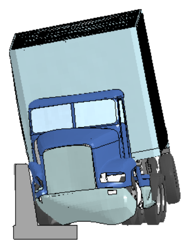
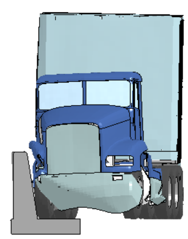
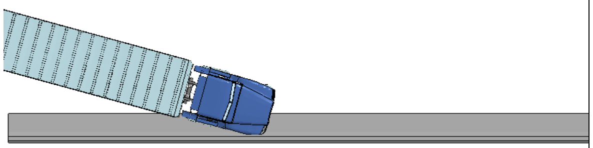
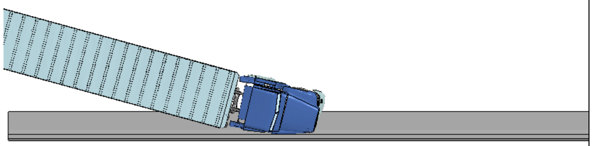
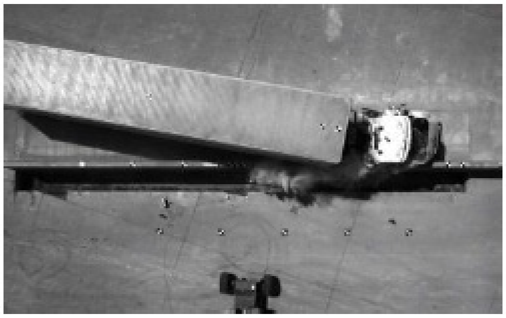
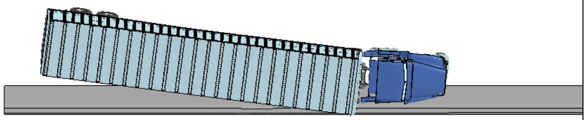
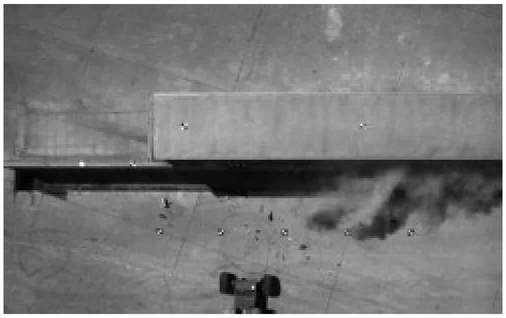
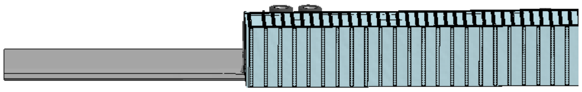
Time (sec)	Test No. MAN-1	Computer Simulation
0		
0.5		
1		
1.25		

Table 19. Frame Comparison of Full-Scale Crash Test (MAN-1) and Computer Simulation – Top View

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

Appendix B

Concrete Median Barrier

System Description

The Concrete median barrier consists of 864 mm (34 in) tall vertical faces with a slight slope of 3.2° for constructability, and base width of 613 mm (24.1 in) [8]. The barrier also includes 203 mm (8 in) tall protrusion above the vertical faces, with top width of 102 mm (4 in), in order to satisfy the head ejection criteria. Concrete mix with minimum compressive strength of 27.6 MPa (4,000 psi) and Grade 60 rebar was used for the test installation (Test No. TL5CMB-2). The barrier end sections had No. 6 stirrups that extended into the 3.66 m x 1.22 m x 0.61 m (12 ft x 4 ft x 2 ft) footer below. The interior section stirrups were held in position using dowel bars. The 60.88 m (199.75 ft) long barrier was placed in a pit with crushed limestone fill and 76 mm (3-in) asphalt overlay was placed on both sides of the barrier face [8].

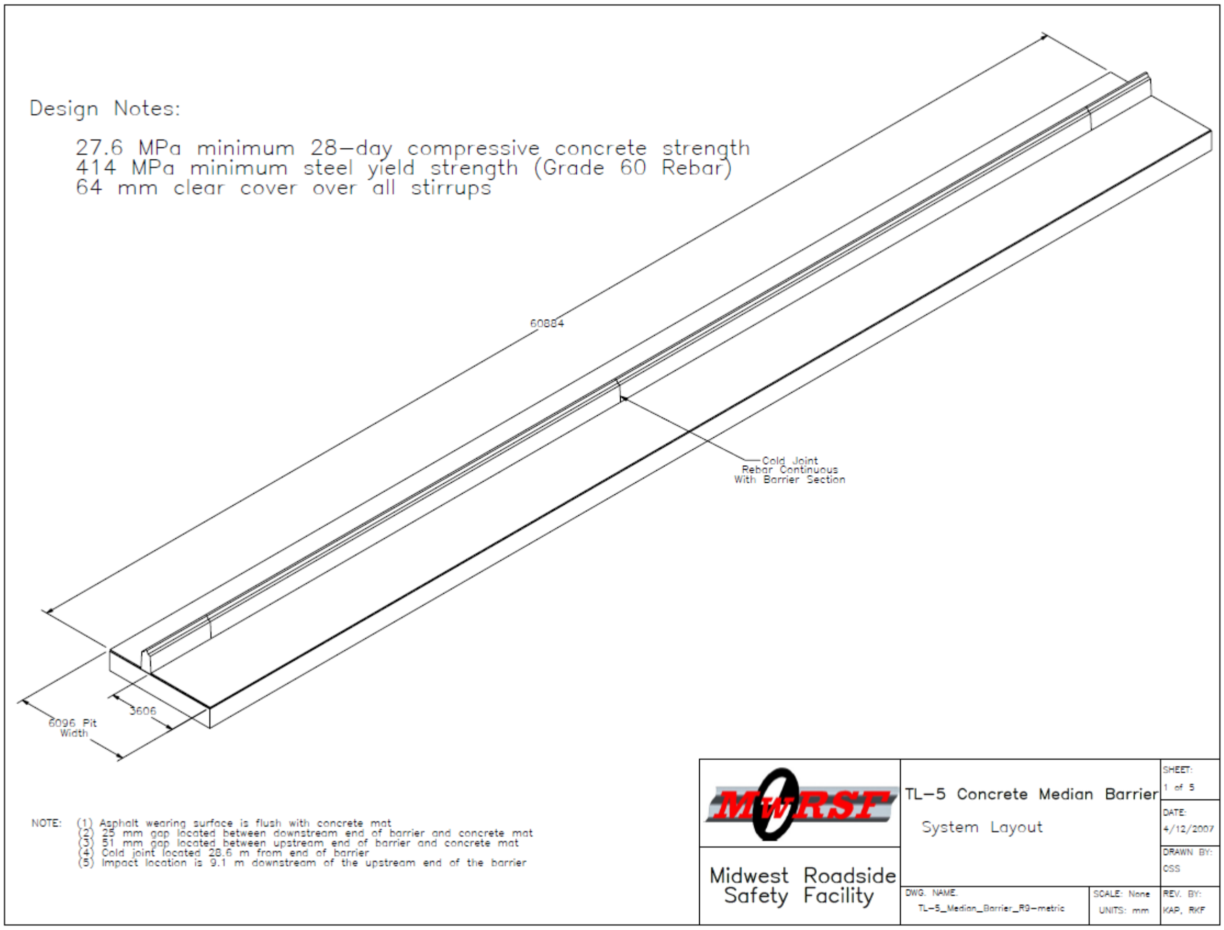


Figure 19. Test installation layout, Test No. TL5CMB-2 [8].

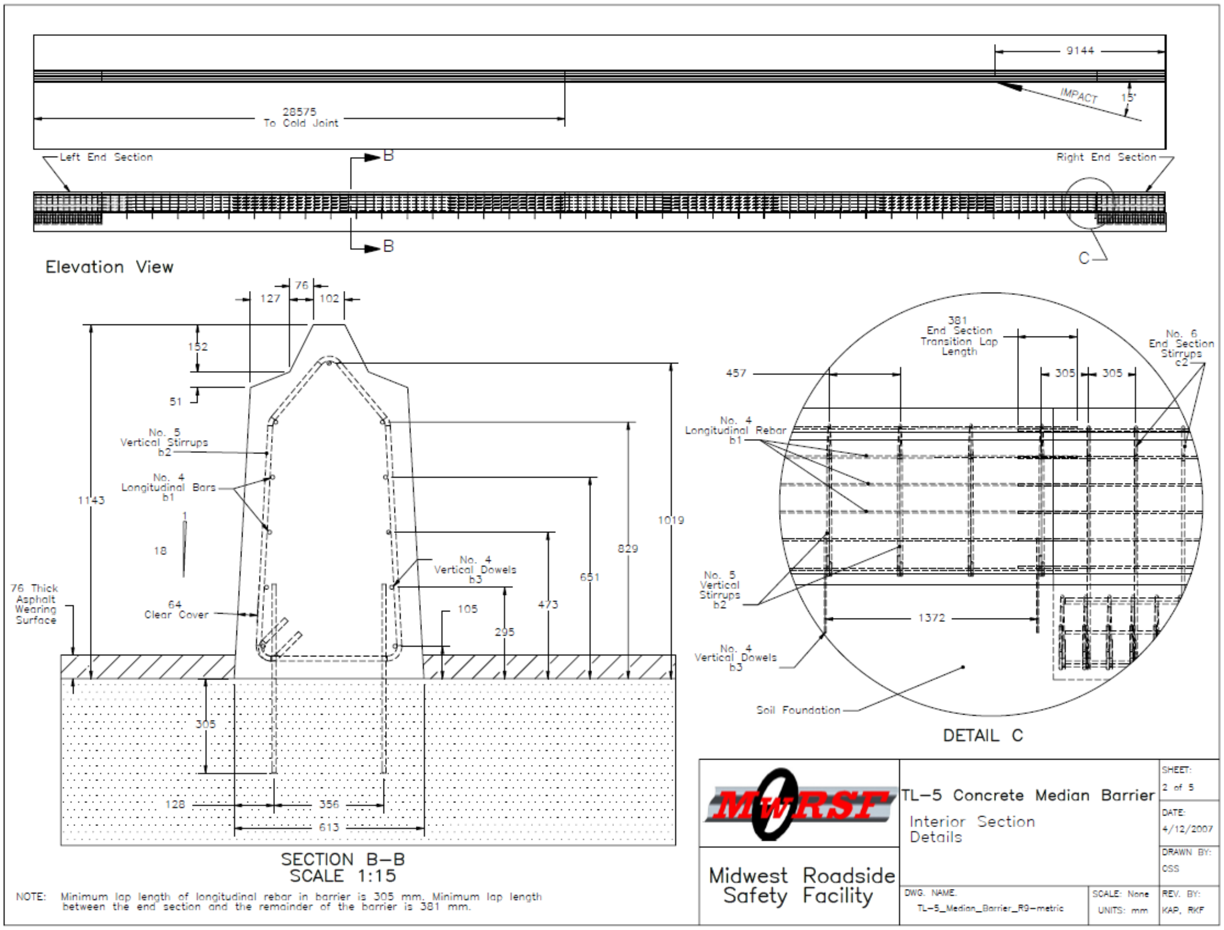


Figure 20. Layout detail, Test No. TL5CMB-2 [8].

The Concrete median barrier was modeled in LS-Dyna as a single 60.88 m (199.75 ft) long barrier segment to simulate the full-scale crash test. 38 mm x 38 mm (1.5 in x 1.5 in) constant stress solid brick elements 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 [6]. The Young's modulus of elasticity of 200,000 MPa (29,000 ksi), Poisson's ratio of 0.3 and yield strength of 413.7 MPa (60 ksi) was specified. Failure strain of 20% was set for the rebar so that the beam element is deleted from calculation after the plastic strain reaches this value. Constrained_Beam_In_Solid (CBIS) card was used to constrain the reinforcing steel in concrete [6]. MAT_CSCM_Concrete (MAT_159) was used to model the concrete [6]. The compressive strength of 39.1 MPa (6,218 psi), which is the measured concrete strength from the full-scale crash test, and default material parameter options were used to define the material card for the concrete model. The footers below the end sections were not modeled and the barrier was considered fixed at those locations. The barrier interior section was placed on top of a rigid base, with static friction of 0.6 and dynamic friction of 0.55 between the barrier concrete and the base. The asphalt overlay was modeled using MAT_Mohr_Coulomb_Title card. The concrete model was allowed to erode during the impact and MAT_Add_Erosion card was used to define the concrete erosion parameters [6]. After running multiple simulations with various parameters, 9.9% effective plastic strain criterion was observed to develop concrete erosion comparable to the TL5CMB-2 full-scale crash test.

1991 White GMC Conventional WG65T tractor with 1988 Pines 48 ft trailer was used to test the Concrete median barrier [8]. The tractor-van trailer FEA model used in Manitoba concrete bridge rail simulations was used to simulate the Concrete median barrier impacts as well.

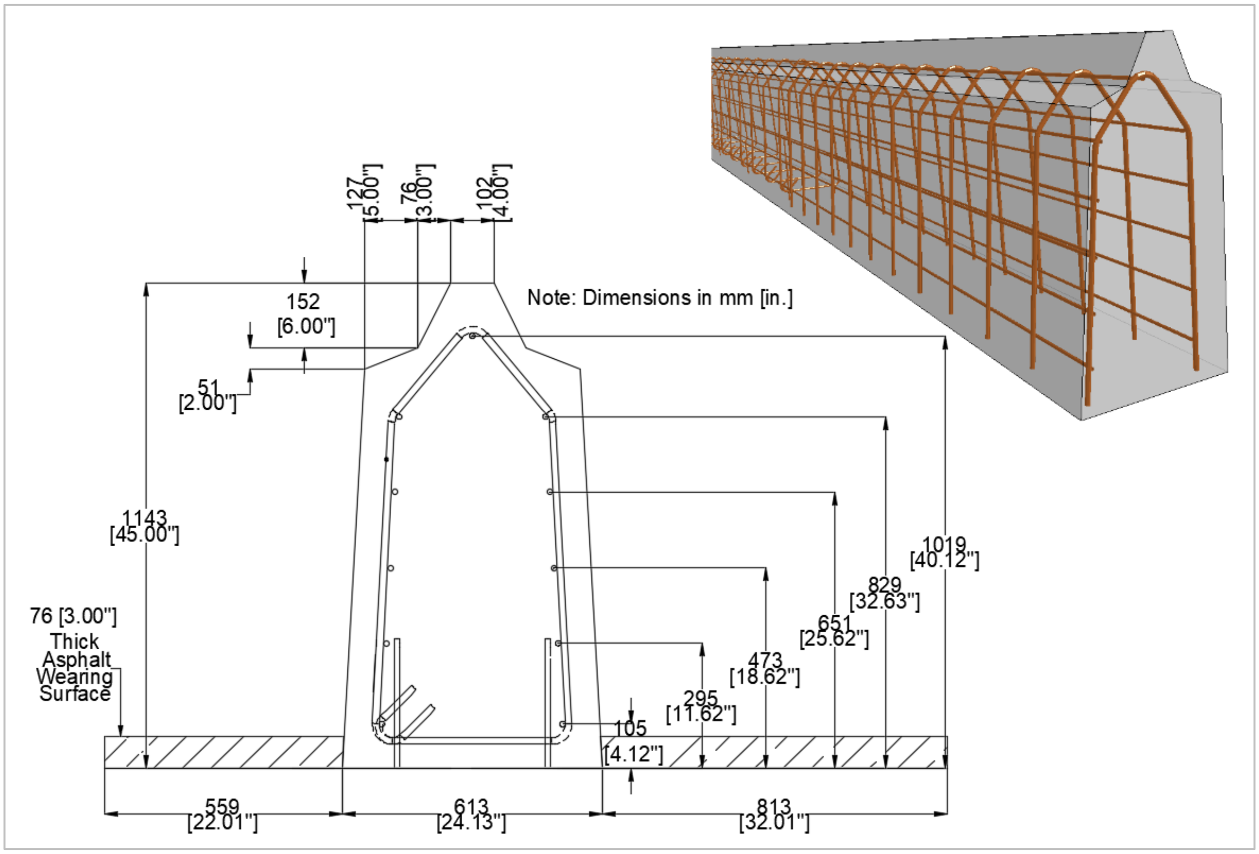


Figure 21. Cross-section and layout of concrete median barrier FEA model.

VALIDATION/VERIFICATION REPORT
FOR

A ____________________Report 350 Tractor-Trailer_________________________________
(Report 350 or MASH08 or EN1317 Vehicle Type)

Striking a ____________TL5 Vertical Faced Concrete Median Barrier______________________
(roadside hardware type and name)

Report Date: _________02-19-2018____

Type of Report (check one)

☐ Verification (known numerical solution compared to new numerical solution) or
☒ Validation (full-scale crash test compared to a numerical solution).

General Information	**Known Solution**	**Analysis Solution**
Performing Organization	MWRsF	TTI
Test/Run Number:	TL5CMB-2	TTI_TL5CMB-2_RUN-1
Vehicle:	1991 White GMC Tractor, 1988 Pines 48 ft Trailer	Tractor Version 2010-03-02 and Trailer Model Version 10-0304
Impact Conditions		
Vehicle Mass:	36,154 kg (79,706 lb)	36,170 kg (79,741 lb)
Speed:	84.9 km/h (54.75 mph)	84.9 km/h (54.75 mph)
Angle:	15.4 deg.	15.4 deg
Impact Point:	9.1 m (29.9 ft) from Upstream End	9.1 m (29.9 ft) from Upstream End

PART I: BASIC INFORMATION

These forms may be used for validation or verification of roadside hardware crash tests. If the known solution is a full-scale crash test (i.e., physical experiment) then the procedure is a validation exercise. If the known solution is a numerical solution (e.g., a prior finite element model using a different program or earlier version of the software) then the procedure is a verification exercise.

Provide the following basic information for the validation/verification comparison:

1. What type of roadside hardware is being evaluated (check one)?
   ☒ Longitudinal barrier or transition
   ☐ Terminal or crash cushion
   ☐ Breakaway support or work zone traffic control device
   ☐ Truck-mounted attenuator
   ☐ Other hardware: ____

2. What test guidelines were used to perform the full-scale crash test (check one)?
   ☒ NCHRP Report 350
   ☐ MASH08

☐ EN1317
☐ Other: ____

3. Indicate the test level and number being evaluated (fill in the blank). ___ ____5-12_____

4. Indicate the vehicle type appropriate for the test level and number indicated in item 3 according to the testing guidelines indicated in item 2.

NCHRP Report 350/MASH08

☐ 700C	☐ 820C	☐ 1100C
☐ 2000P	☐ 2270P	
☐ 8000S	☐ 10000S	
☒ 36000V		
☐ 36000T		

EN1317

☐ Car (900 kg)	☐ Car (1300 kg)	☐ Car (1500 kg)
☐ Rigid HGV (10 ton)	☐ Rigid HGV (16 ton)	☐ Rigid HGV (30 ton)
☐ Bus (13 ton)		
☐ Articulated HGV (38 ton)		

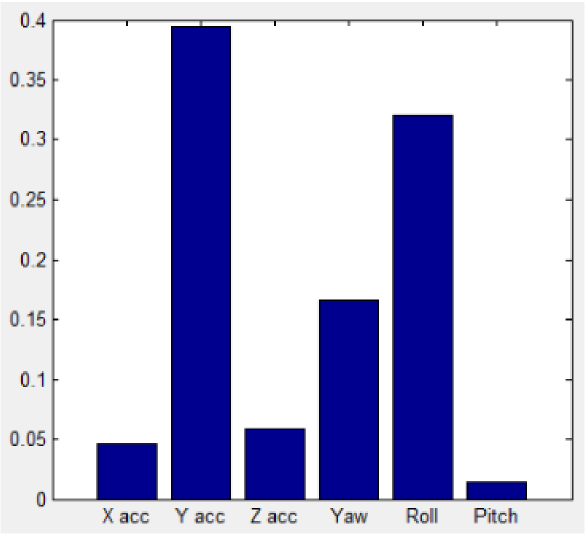
Table 20. Analysis Solution Verification Table – Concrete Median Barrier

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	10	YES
Hourglass Energy of the analysis solution at the end of the run is less than five percent of the total initial energy at the beginning of the run.	0.16	YES
Hourglass Energy of the analysis solution at the end of the run is less than ten percent of the total internal energy at the end of the run.	2.1	YES
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run.	11.5	**Border-line***
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0.1	YES
The part/material with the most mass added had less than 10 percent of its initial mass added.	4.6	YES
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	4.6	YES
There are no shooting nodes in the solution?	Yes	YES
There are no solid elements with negative volumes?	Yes	YES

**The hourglass energy to total internal energy ratio of the concrete was 11.5% which is larger than the suggested value. It was assumed that the numerical erosion of the concrete had some effect on the hourglass behavior. The response of the barrier was very similar to the full-scale crash test. The global energy of the system was stable and the hourglass effect decreased to below 10% for the following truck impacts.*

The Roadside Safety Verification and Validation Program (RSVVP) was used for the purpose of quantitatively validating the numerical model [9, 10]. The full-scale crash test data from the principle event data recorder (EDR) accelerometer and rate sensor units were provided by MwRSF, the unit was mounted near the tractor tandem axles [8]. The secondary EDR unit mounted near the tractor tandem axles did not record any data due to technical issues [8]. Acceleration and angular displacement data were compared between the test and simulation according to Sprague and Geers (S&G) metrics and variance (ANOVA) metrics. The data from the simulation was filtered in LS-Dyna using SAE 180 filter. The evaluation was performed over a period of 1.77 s of the impact event. The acceptance criteria are maximum value of 40 for S&G metrics, 35% for ANOVA standard deviation and 5% for ANOVA mean [9, 10]. Summary of quantitative multi-channel time history comparison of TL5CMB-2 test data and FEA are shown in Table 21. The results were in good agreement even though the mean residual ANOVA metric was considered borderline.

Table 21. Quantitative Multi-Channel Time History Comparison of Test vs FEA – Principle EDR Unit

<table>
<tr><th colspan="5">Evaluation Criteria (time interval [0 sec; 1.77 sec])</th></tr>
<tr><td colspan="5">Channels (Select which was used)</td></tr>
<tr><td colspan="2">☒ X Acceleration</td><td>☒ Y Acceleration</td><td colspan="2">☒ Z Acceleration</td></tr>
<tr><td colspan="2">☒ Roll rate</td><td>☒ Pitch rate</td><td colspan="2">☒ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weighting Method</td><td>☐ Peaks
☐ Area I
☒ Area II
☐ Inertial</td><td colspan="2">Channel Weight Factors

</td></tr>
<tr><td rowspan="2">O</td><td rowspan="2" colspan="2">Sprauge-Geer Metrics
Values less or equal to 40 are acceptable.</td><td>M</td><td>P</td></tr>
<tr><td>39.7</td><td>27.1</td></tr>
<tr><td rowspan="2">P</td><td rowspan="2" colspan="2">ANOVA Metrics
Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration
($\bar{e} \leq 0.05 \cdot a_{Peak}$)
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td></tr>
<tr><td>-5.8*</td><td>15.1</td></tr>
</table>

** According to the results, the FEA model was only in marginal agreement with the full-scale crash test. As the acceptance criteria is developed from results of multiple tests involving a car, these criteria can be considered to be strict for the tractor-van trailer impact event which is a longer multi-body impact compared to a car impact. So, the ANOVA Mean Residual result was considered to be on the borderline for this assessment. It was noted that similar approach was followed on some previous studies for validation of a tractor-van trailer.*

Table 22. Evaluation Criteria Test Applicability Table – Concrete Median Barrier

<table>
<tr><th>Evaluation Factors</th><th colspan="2">Evaluation Criteria</th><th>Applicable Tests</th></tr>
<tr><td rowspan="2">Structural Adequacy</td><td>A</td><td>Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38</td></tr>
<tr><td>B</td><td>The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>60, 61, 70, 71, 80, 81</td></tr>
<tr><td></td><td>C</td><td>Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>30, 31,, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53</td></tr>
<tr><td rowspan="6">Occupant Risk</td><td>D</td><td>Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>All</td></tr>
<tr><td>E</td><td>Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle. (Answer Yes or No)</td><td>70, 71</td></tr>
<tr><td>F</td><td>The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>All except those listed in criterion G</td></tr>
<tr><td>G</td><td>It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>12, 22 (for test level 1 – 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44)</td></tr>
<tr><td>H</td><td>Occupant impact velocities should satisfy the following:<table><tr><th colspan="3">Occupant Impact Velocity Limits [ft/s (m/s)]</th></tr><tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr><tr><td>Longitudinal and Lateral</td><td>30 (9.1)</td><td>40 (12.2)</td></tr><tr><td>Longitudinal</td><td>10 (3.0)</td><td>15 (4.9)</td></tr></table></td><td>Longitudinal and Lateral: 10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81
Longitudinal: 60, 61, 70, 71</td></tr>
<tr><td>I</td><td>Occupant ridedown accelerations should satisfy the following:<table><tr><th colspan="3">Occupant Ridedown Acceleration Limits (g's)</th></tr><tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr><tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr></table></td><td>10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td rowspan="3">Vehicle Trajectory</td><td>L</td><td>The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec (12.2 m/sec) and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.</td><td>11,21, 35, 37, 38, 39</td></tr>
<tr><td>M</td><td>The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39</td></tr>
<tr><td>N</td><td>Vehicle trajectory behind the test article is acceptable.</td><td>30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81</td></tr>
</table>

Table 23. Roadside Safety Phenomena Importance Ranking Table – Concrete Median Barrier

Evaluation Criteria				Known Result	Analysis Result	Relative Diff. (%)	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		Yes
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	38 mm (1.50 in)	18 mm (0.71 in)	52.6%	**No***
		A3	The relative difference in the length of vehicle-barrier contact is less than 20 percent.				
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	NA	NA	NA	NA
		A5	The rail element did not rupture or fail (Answer Yes or No)	NA	NA		NA
		A6	There were no failures of connector elements (Answer Yes or No).	NA	NA		NA
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	No	No		Yes
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	No	No		Yes
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Yes or No)	Pass	Pass		Yes
	G	G1	It is preferable, although not essential, that the vehicle remain upright during and after collision. (Answer Yes or No)	Pass	Pass		Yes
		G2	The relative difference in the maximum vehicle roll angle is less than 20 percent.	38.32	35.2	8.14%	Yes
		G3	The relative difference between the maximum rotation between the tractor and trailer is less than 20 percent (Tests 5-12, 6-12, 5-22 and 6-22 only			NA	NA
		G4	The vehicle ballast or load significantly shifted during the collision (Tests 12 and 22 only)				Yes
		G5	The frontal axle connection failed (Tests 12 and 22 only).				
	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	Yes	Yes	NA	Yes
		M2	The relative difference in the exit angle at loss of contact is less than 20 percent.	0	0	0	Yes
		M3	The relative difference in the exit velocity at loss of contact is less than 20 percent.	NA	NA	NA	NA
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	No	No		Yes
		M5	One or more tires separated from the vehicle (Answer Yes or No).	No	No		Yes

**The dynamic displacement of the barrier was about 20mm larger in the full-scale crash test when compared to the simulation results. However, 38 mm deflection during the full-scale crash test implies that the barrier displayed a fairly rigid behavior. It was noted that the percent difference criteria can be very sensitive for these small deflection values [9]. As the difference in maximum deflection was below 1 in, the result was considered to be reasonable.*

The sequential snapshots from the full-scale crash test were compared to the FEA analysis as a part of qualitative evaluation of the model validity. Table 24 and Table 25 show the frame comparison from test no. TL5CMB-2 and computer simulation starting at zero second, i.e. the time of first contact between tractor-trailer and the barrier during impact event. The kinematic response of the FEA vehicle was in good agreement with the full-scale crash test vehicle and the phenomenological events from the full-scale crash test were well replicated by the FEA. As stated previously, the acceptance criteria are developed from results of multiple tests involving a car, these criteria can be considered strict for the tractor-van trailer impact event which is a longer multi-body impact compared to a car impact. The results of the quantitative validation only marginally met the default requirements; however, the simulation was deemed satisfactory based on overall quantitative and qualitative evaluation.

Table 24. Frame Comparison of Full-Scale Crash Test (TL5CMB-2) and Computer Simulation – Front View

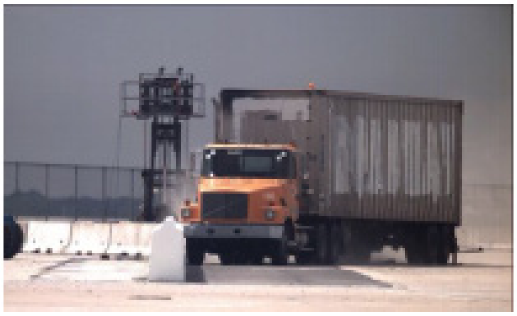
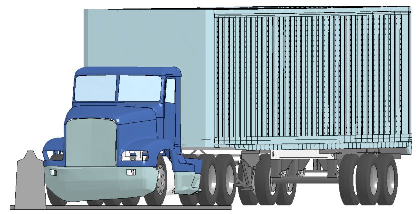
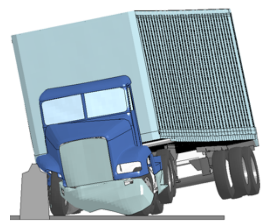
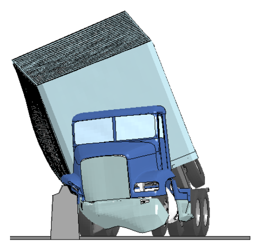
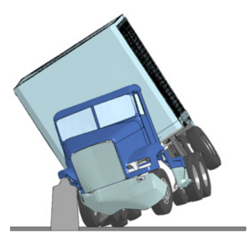
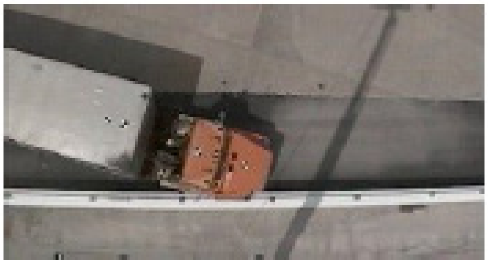
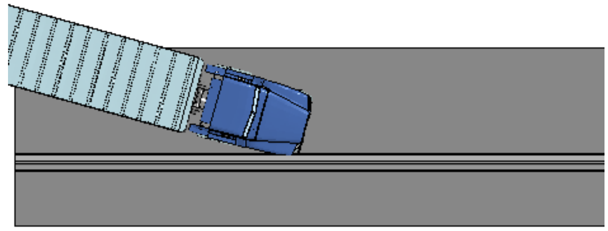
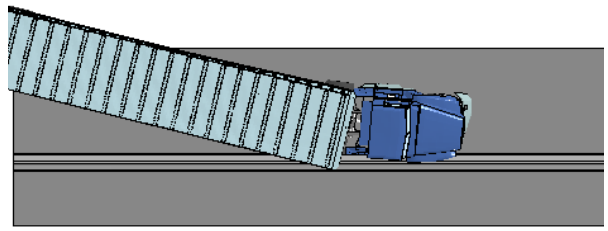
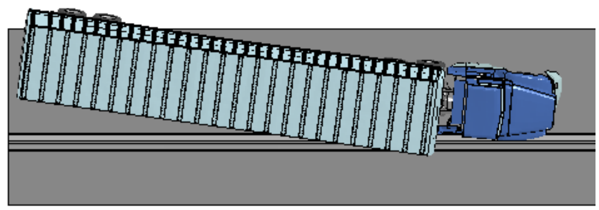
Time (sec)	Test No. MAN-1	Computer Simulation
0		
0.4		
0.78		
1.16		

Table 25. Frame Comparison of Full-Scale Crash Test (TL5CMB-2) and Computer Simulation – Top View

Time (sec)	Test No. MAN-1	Computer Simulation
0		
0.24		
0.4		
0.56