FINITE ELEMENT ANALYSIS OF TRUCK PLATOON IMPACT INTO ROADSIDE

SAFETY BARRIERS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2018

Major Subject: Civil Engineering

ABSTRACT

Platooning is an extension of Cooperative Adaptive Cruise Control (CACC) and forward collision avoidance technology that provides automated lateral and longitudinal vehicle control to maintain a tight formation with short following distances. A truck platoon is led by a manually driven truck while the drivers of the following trucks can disengage from driving tasks, but remain alert and monitor the performance of the system. As platooning is a new technology, it is necessary to understand whether the capacity of existing roadside safety devices is adequate to resist the potential multiple impacts due to errant truck platoons. It is also important to know how the errant platoons will behave, and what are the risks imposed to the occupants as well as other motorists during and after such impacts.

As full-scale crash test can be expensive and time consuming, finite element analysis (FEA) can be a valuable tool to simulate and assess the roadside impact events. LS-DYNA is a very popular software for explicit FEA analysis in roadside safety community. This project will utilize computer simulations in LS-DYNA to understand the adequacy of the critical roadside safety devices, vehicle stability and occupant risks during errant truck platoon impacts. Truck platoon impact into two representative reinforced concrete barriers are analyzed in this study under Manual for Assessing Safety Hardware (MASH) Test Level 5 (TL5) criteria. The minimum truck platoon fleet size that the existing roadside safety devices can handle without any design changes can be potentially predicted. Also, the results will indicate if any roadside safety device improvements and/or platooning constraint modifications will be necessary to ensure safety of occupants as well as other motorists, pedestrians and/or work zone personnel before truck platooning can be deployed.

CONTRIBUTORS AND FUNDING SOURCES

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1. INTRODUCTION<superscript>*</superscript>

Platooning is an extension of Cooperative Adaptive Cruise Control (CACC) and forward collision avoidance technology. It provides automated lateral and longitudinal vehicle control to maintain short following distances and tight formation. A manually driven truck leads the platoon that allows drivers of the following trucks to disengage from driving tasks, but remain alert and monitor the performance of the system. As truck platooning is a transformative technology under development stage, it is yet to be deployed in the United State as well as Europe. There are various ongoing research works that are focusing on truck platooning vehicle-to-vehicle (V2V) communication system. If truck platooning is to be deployed within a decade, it is important to understand whether the capacity of existing roadside safety devices is adequate to resist the potential multiple impacts due to errant truck platoons. However, there is no known data on the adequacy of the roadside safety devices in case of errant truck platoons due to the loss of V2V communication. It is also necessary to know the risks imposed to the occupants as well as other motorists during and after such impacts.

As there are various categories of roadside safety devices including flexible, rigid, semi-rigid, redirective, non-redirective and breakaway devices designed to serve a specific purpose, the device categories should be prioritized for further evaluation based on identified potential risks to motorists. It is also necessary to identify the critical roadside safety devices that are currently

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<superscript>*</superscript> Part of the data reported in this section is reprinted from "Evaluation of the Injury Risks of Truck Occupants Involved in a Crash as a Result of Errant Truck Platoons" by Jin, H., Sharma, R., Meng, Y., Untaroiu, A., Dobrovolny, C.S., and Untaroiu, C., 2018. 15th International LS-DYNA Users Conference, pp. 1-16.

deployed at locations where truck platooning might be allowed. For economic reasons, many existing barrier systems are optimized for the current design impact conditions and have little or no factor of safety for accommodating more severe impacts. Most critical Manual for Assessing Safety Hardware (MASH) – Test Level 5 (TL5) roadside safety devices will be examined under the scope of this research as tractor-van trailers for truck platooning impact assessment fall under this category [1]. Considering the associated risks and likeliness of the impact scenarios, TL5 concrete bridge rails and TL5 concrete median barriers were identified as the most appropriate roadside safety features for impact assessment. This research cannot include and test all configurations of TL5 devices, however, it will provide implications if tests will be necessary on all or any additional devices with similar or lesser capacity based on results of the simulated roadside devices. The minimum truck platoon fleet size that the existing roadside safety devices can handle without any design changes can be potentially predicted. Also, the results will imply if any roadside safety device improvements and/or platooning constraint modifications will be necessary to ensure safe implementation.

Injuries to the truck occupant themselves is always one of the major topics of interest. Depending on the environmental conditions, perception-reaction time of the following truck operators and behavior of truck platoon after communication failure, injuries to the occupant may be serious or even fatal. Within MASH criteria, flail space model (FSM) concept is utilized to assess occupant risk [2]. It will allow us to understand if the truck platooning will be safe in terms of occupant safety. Additional safety features may be necessary involving modifications to the cabin.

As implementation of full-scale crash tests to replicate the MASH TL5 impacts can be expensive and time consuming, finite element analysis (FEA) can be a valuable tool to simulate

and assess these roadside impact events. LS-DYNA, a popular software for explicit FEA analysis in roadside safety community, will be utilized to simulate the impact events in this study. Ideally, full-scale crash tests should be performed to validate the simulation results. However, full-scale crash tests will not be performed under the scope of this research considering the preliminary nature and scope of this research. Based on the evaluation of results, recommendations will be made which include suggested roadside safety device improvements, platooning constraint modifications and additional research before truck platooning is deployed.

The objectives of this research are:

a. to assess the structural adequacy of the selected critical roadside devices during the event of errant truck platoon impacts using computer simulations,

b. to assess the stability of the impacting trucks,

c. to assess risks imposed to occupants using MASH criteria.

2. BACKGROUND

2.1 Truck Platooning and V2V Communication Technology

Research and development on autonomous trucks and platooning started as early as two decades ago, however the major progress in platooning has been made in past five years [3]. This technology is new and under development phase not only in US but also Europe. Application of platooning is ideal for trucks as they usually travel long distances on high speed roadways in groups. Truck platooning is a long-term vision to improve freight system while maintaining roadside safety and fuel efficiency up to 6.4 percent [4]. Team fuel savings that was determined by adding the savings from both leading and trailing vehicle for two-truck platoon from a study is shown in Figure 1 [4]. It can be observed that the best combined fuel savings from the range of 3.7% to 6.4% was observed at speed of 55 mph and following distance of 30 ft. The widespread adoption of platooning operations for combination trucks in the United States could lead to a total savings of 1.5 billion gallons of petroleum derived fuels (equal to 1.1% of the current US import of oil) and 15.3 million metric tons of CO_2 (a 0.22% emissions reduction) [5]. This was based on the fact that approximately 65.6% of the total miles driven by class 7 and 8 trucks could be driven in a form of platoons, it is also estimated that the percentage will eventually increase to approximately 76.6% [5].

The US army is involved in development of truck platooning technology and has conducted a number of demonstrations [3]. Private firms like Peloton are also actively involved in research and development of truck platooning. US Federal Highway Administration (FHWA) and the Texas Department of Transportation (TxDOT) are intending to deploy commercial two-truck platoon at specific routes in Texas within a decade [6]. Texas A&M Transportation Institute (TTI) recently

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hosted a successful two-truck platooning technology demonstration at Texas A&M University System RELLIS campus in July 2016 [6]. This demonstration was first of its kind in Texas, and it was only a part of first phase out of three phases that need to be successfully accomplished before truck-platooning can be implemented [7]. Ricardo, Navistar, TRW, Denso, Bendix, GreatDane Trailer, Lytx, Argonne National Laboratory and U.S. Army TARDEC are the private partners involved along with TTI in the project [6]. As the technology is still in initial phase, the review of relevant federal and state regulations as well as liability issues is also involved.

The risks involved in multiple impacts into roadside devices at very small interval of time and at very close locations which can occur due to errant truck platoons can be assumed to be a lot higher than a single tractor-van trailer impact. Errant trucks running over a construction site after failure of roadside safety device and causing major injuries or fatalities to the work site personnel can be considered as an example of an undesired scenario. So, it is critical to study the adequacy of the roadside devices to avoid major fatalities. The roadside devices must contain and redirect the impacting vehicles without causing rollover, i.e. the impacting vehicle should maintain stability during and after impact. Considering the limited progress in platooning technology itself, there is no known data on impact of truck platoon into roadside devices or the risk associated to the occupant and other motorists during such events.

The following trucks in a truck platoon are usually controlled by V2V communication, malfunction of which should be studied to understand the various possible impact scenarios. V2V technology communicates using omnidirectional (covering 360 degree) radio signals that allow two equipped vehicles to "see" each other at times other vehicles that are only relying on their sensors are not able to detect the presence of another vehicle, let alone determine the other vehicle's heading, speed, or its operational status [10]. Due to lack of known data on the behavior

of following trucks in the event of errant truck platoons operating under V2V communication, TL5

impact conditions can be conservatively applied to the following trucks as well.
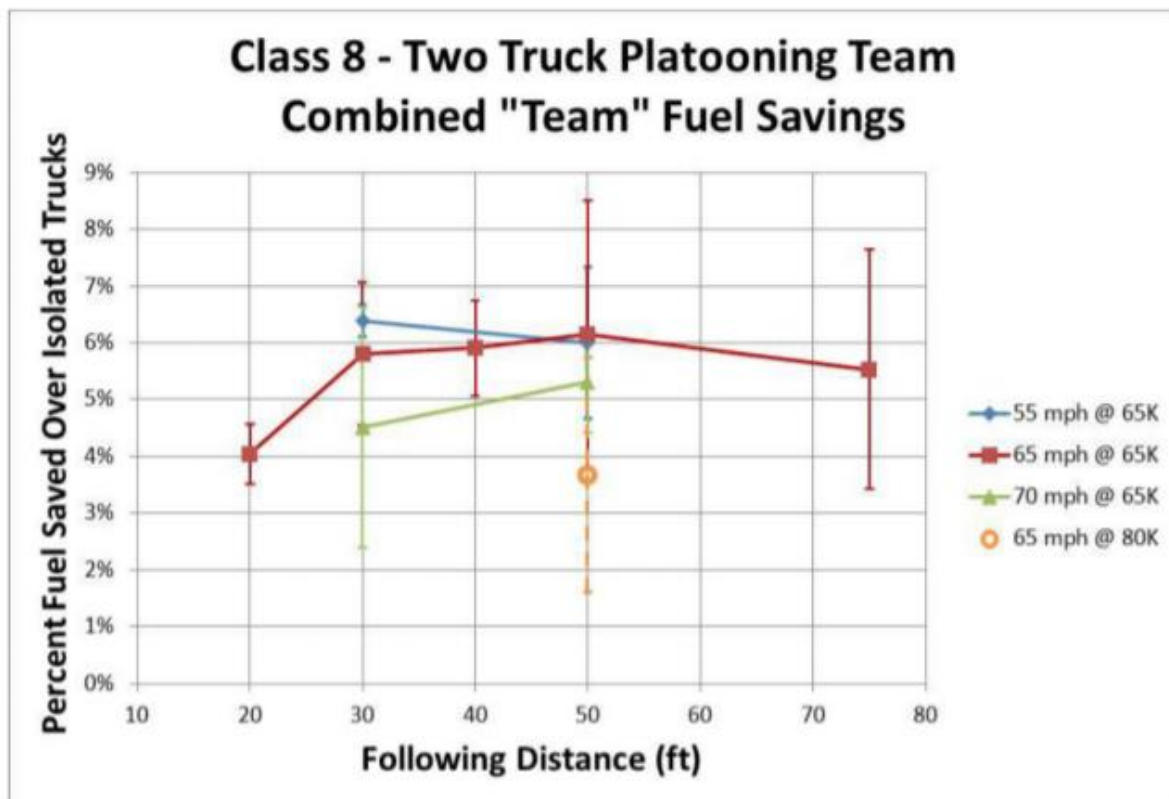
Figure 1. Platoon team percent fuel savings, reprinted from [4]

2.2 MASH Criteria for Impact Testing

Even though there has not been significant research in impact of truck platoon into roadside

devices, there has been extensive research in single tractor-van trailer impact into the roadside

devices, and associated risks to the occupants and roadside motorists. These studies will be a basis

in developing the impact criteria and scenarios for this research. National Cooperative Highway

Research Program (NCHRP) Report 350 which was published in 1993 was the criteria that was

being followed to design the roadside safety devices, however, it has now been updated to MASH as of 2009 [1,8]. MASH 2009 was then superseded by MASH 2016.

Roadside safety devices are placed at areas where it is not practical to remove all obstacles and provide a traversable area for the errant vehicles to recover. Roadside safety device is used only when consequences of impact against the roadside obstruction is deemed more severe than against the safety device. Typical locations where such devices are used include bridge ends, lateral drop-offs, slopes and other terrain features that pose risk of serious injuries. If it is not possible to remove, relocate or avoid roadside obstacles, they are made breakaway, crashworthy or traversable. Use of appropriate roadside safety devices can reduce the risk of injury not only to the vehicle's occupants but also other motorists, pedestrians and/or work zone personnel. Functions of a roadside safety device may be to contain and redirect the vehicle away from roadside obstruction, to safely decelerate the vehicle to a stop, to allow controlled penetration, to break away, yield or fracture, or to allow the vehicle to traverse safely for recovery [1]. Categories of roadside safety devices include breakaway devices, workzone attenuation and channelizers, terminals, crash cushions, longitudinal barriers and others [1].

MASH provides guidelines to perform vehicular crash tests in order to examine the performance of various roadside safety features [1]. The testing parameters are based on worst conditions that can be expected in real world scenarios, while keeping the cost-effectiveness and desired level of safety in mind. As per MASH guidelines, testing criteria for longitudinal barriers ranges from Test Level 1 (TL1) to Test Level 6 (TL6), whereas all other roadside safety devices may be tested from TL1 to Test Level 3 (TL3). Different test levels are designed based on the impact speed and angle of approach and testing vehicle type ranging from small cars to fully loaded tractor-trailer truck. TL1 to TL3 involve passenger vehicles only. Test Level 4 (TL4) to TL6

involve some form of heavy truck. Typically, roadside safety features that are designed for lower test levels are intended for use in low-speed and/or low-volume roadways whereas the features designed for higher test levels are generally used in high-speed and/or high-volume roadways. Different roadside safety devices designed for same test level can have different applications, therefore they can have different design needs and performance characteristics (rigid or flexible, redirective or non-redirective). Design, application and expected post-impact behavior of different roadside safety devices has to be analyzed to determine the critical roadside devices to be studied under the scope of this particular project [1].

There is a potential that the tractor-van trailers impact against TL1 to TL4 devices such as breakaway devices and crash cushions when truck platooning is deployed. However, as tractor-van trailers fall under TL5 category, only TL5 impacts are considered under the scope of this project. MASH defines TL5 impact as an impact of an 80 kips tractor-van trailer at an angle of 15 degrees and speed of 50 mph [1]. TL5 test criteria are for large trucks on high speed highways, freeways and Interstate highways where a high number of large trucks and unfavorable site conditions can exist [9].

Within MASH criteria, flail space model (FSM) concept is utilized to assess occupant risk [2]. In full-scale crash simulations, the data required for occupant risk assessment – based on theoretical FSM concept of an unrestrained point mass, is collected from the accelerometer modeled at the center of gravity (CG) of the vehicle cabin. Extensive and better-predicting occupant risk assessment can be performed using anthropomorphic test devices (ATDs). ATDs show humanlike response and can predict potential injuries on various regions of the body. However, occupant risk study using ATDs is not presented under the scope of this study.

2.3 Finite Element Analysis (FEA)

Structural adequacy, vehicle stability and occupant risk are the main criteria for the evaluation of roadside devices. FEA programs serve as an important tool in evaluating these criteria. LS- DYNA is one of the most popular explicit FEA code among the researchers in roadside and physical security and was used by the researchers to execute this study [11]. It is capable of analyzing non-linear dynamic response of three-dimensional structures and has been extensively used in crashworthiness simulations of vehicles.

3. METHODOLOGY[*]

3.1 Overall Approach

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 [1]. 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 TL5 barriers, with eligibility letter from Federal Highway Administration (FHWA) as shown in Table 1, 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 representative concrete bridge rail and concrete median barrier respectively [15,16].

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Table 1. List of TL5 Roadside Devices with FHWA Eligibility Letter

Device Name	Sponsor	FHWA No.	Proprietary?
Manitoba Constrained-Width, Tall Wall Barrier	Midwest Roadside Safety Facility	B-268	No
Vertical-Faced, Concrete Median Barrier Incorporating Head Ejection Criteria	Midwest Roadside Safety Facility	B-182	No
MDS- 5 Steel longitudinal barriers/bridge railings	MDS LLC	B-165	Yes
ESB bridge rail	Perini Corporation	B-154	Yes
Bridge Rail	Midwest Roadside Safety Facility /Nebraska Department of Roads	B-145	No
Max-Rail	Composite Structural Design, LLC	B-142	Yes
Sistema (all-steel temporary barrier)	Composite Structural Design, LLC	B-123	Yes
Pennsylvania Bridge Barrier	Pennsylvania Department of Transportation	B-104	No
Various	Various	B-64	No
Fracasso 3N Median Barrier	Fracasso	B-46	Yes

After the most critical roadside devices were determined and representative roadside devices were selected for the study, they were tested for capacity and adequacy. Finite element computer simulations were run in LS-DYNA to evaluate the effect of a truck platooning fleet impacting in series into the selected roadside safety devices. The leading truck impact simulation results were evaluated against the corresponding full-scale crash test results before running the following truck simulations. 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, i.e. 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 [11]. 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

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the initial conditions for the additional following impacts. On the other hand, as there has not been any substantial research on the behavior of the errant truck platoons, there is no known data on the angle and speed at which the following trucks that leave the platoon will impact the roadside barriers. So, the impact conditions (speed, angle and location) defined by MASH for TL5 were used for the following truck impacts as well.
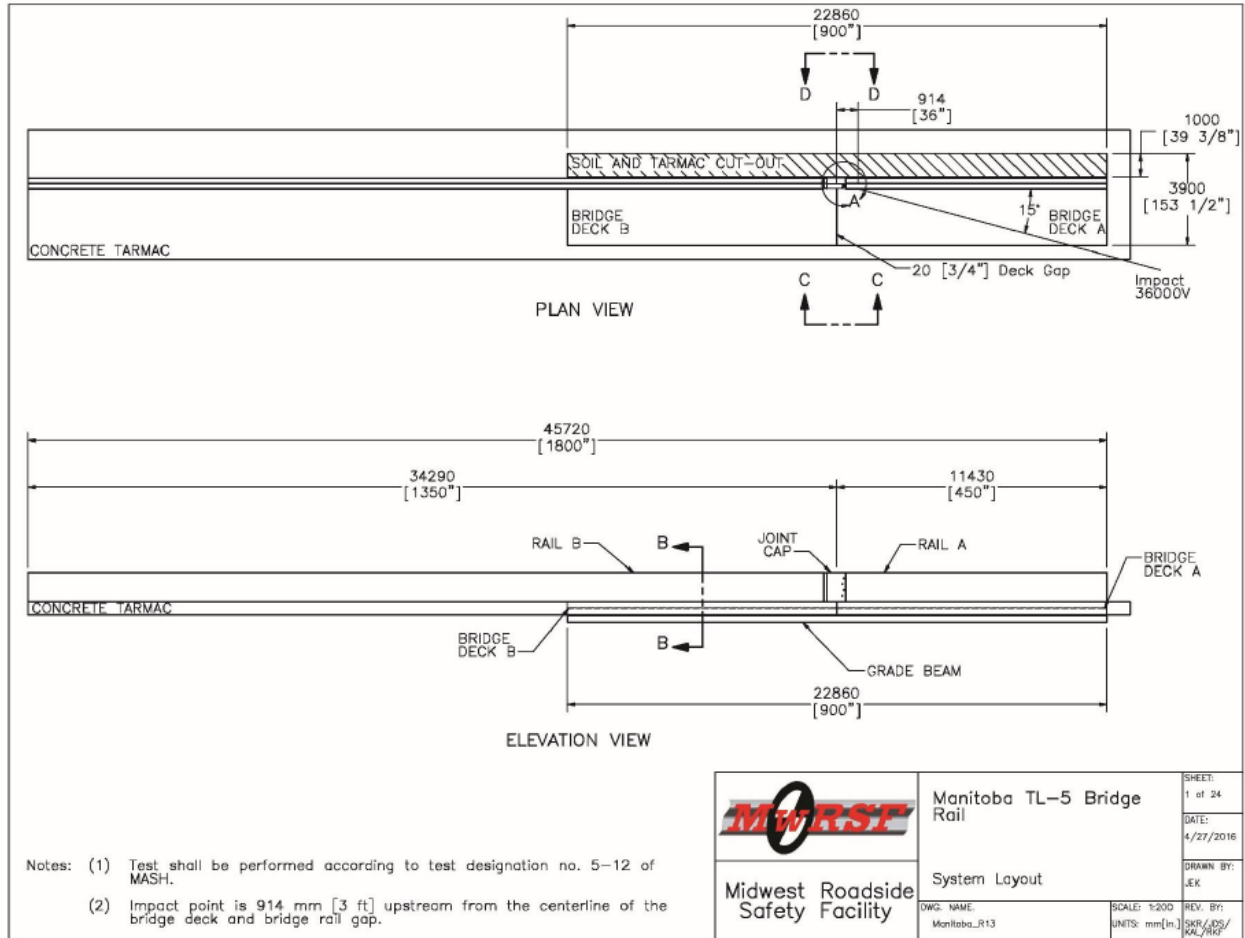
Based on the barrier damage and impacting vehicle behavior during and after the impact simulations, the structural adequacy of the barrier and vehicle stability were assessed under MASH TL5 criteria. The occupant risk metrics were calculated using Test Risk Assessment Program (TRAP) from the collected data [17]. Criteria defined by MASH was used to assess the occupant risk. Then, the results were analyzed to make conclusions and recommendations.

3.2 System Description

The details of the Manitoba concrete bridge rail (Test No. MAN-1) and Concrete Median barrier (Test No. TL5CMB-2) from the full-scale crash tests were used to develop the FEA models used in the simulations [15, 16]. In addition, an existing proprietary tractor-van trailer FEA model was used in the simulations after minor adjustments. The systems used in the full-scale crash tests and the FEA models used in the simulations are discussed below.

3.2.1 Manitoba Concrete Bridge Rail

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) [15]. 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 full-scale crash test installation of the concrete bridge rail and deck [15]. The 45.72 m (150 ft) long full-scale crash 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) [15]. The full-scale crash test installation layout and layout details for the Manitoba concrete bridge rail are shown in Figure 2 and Figure 3 [15].

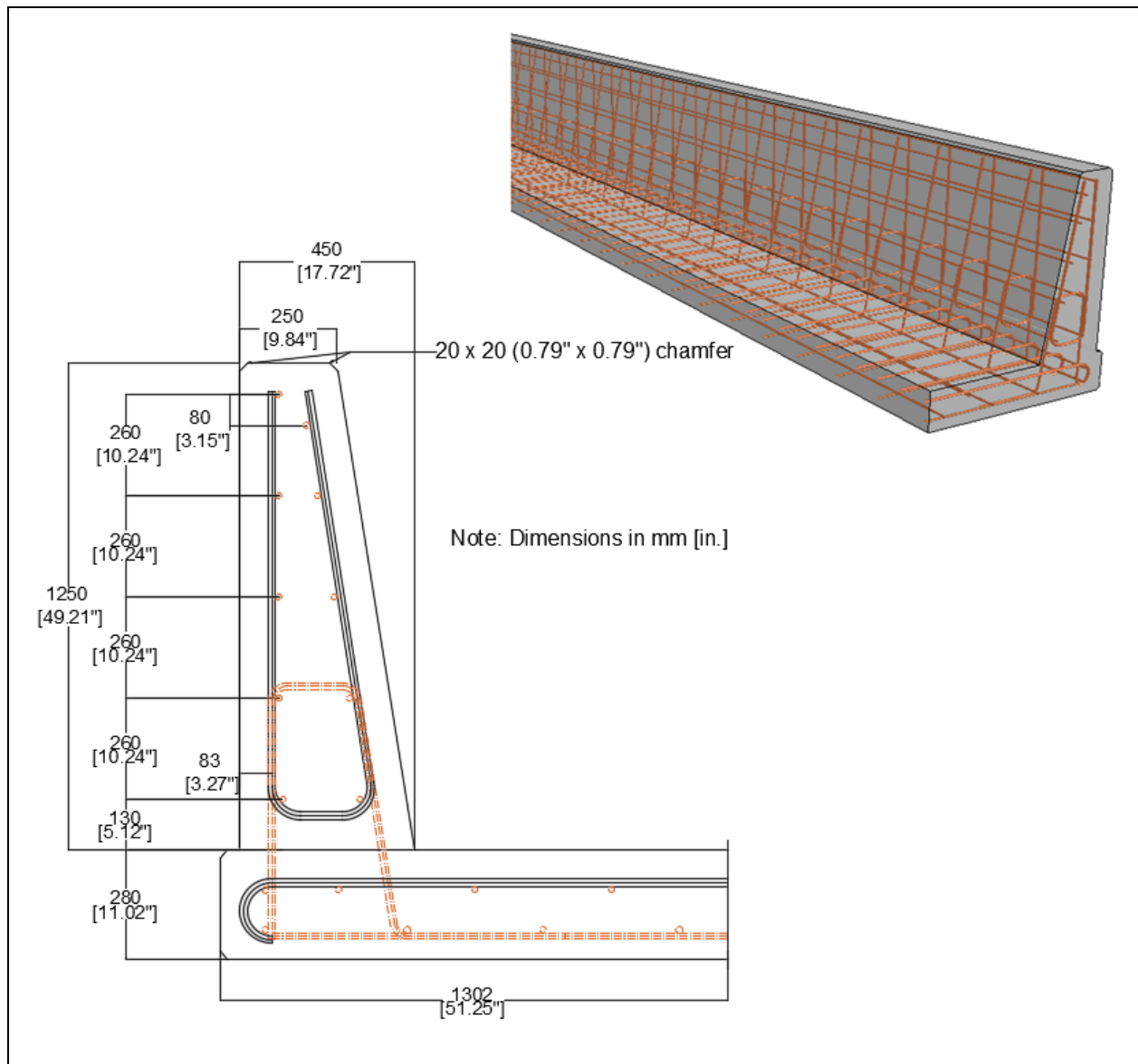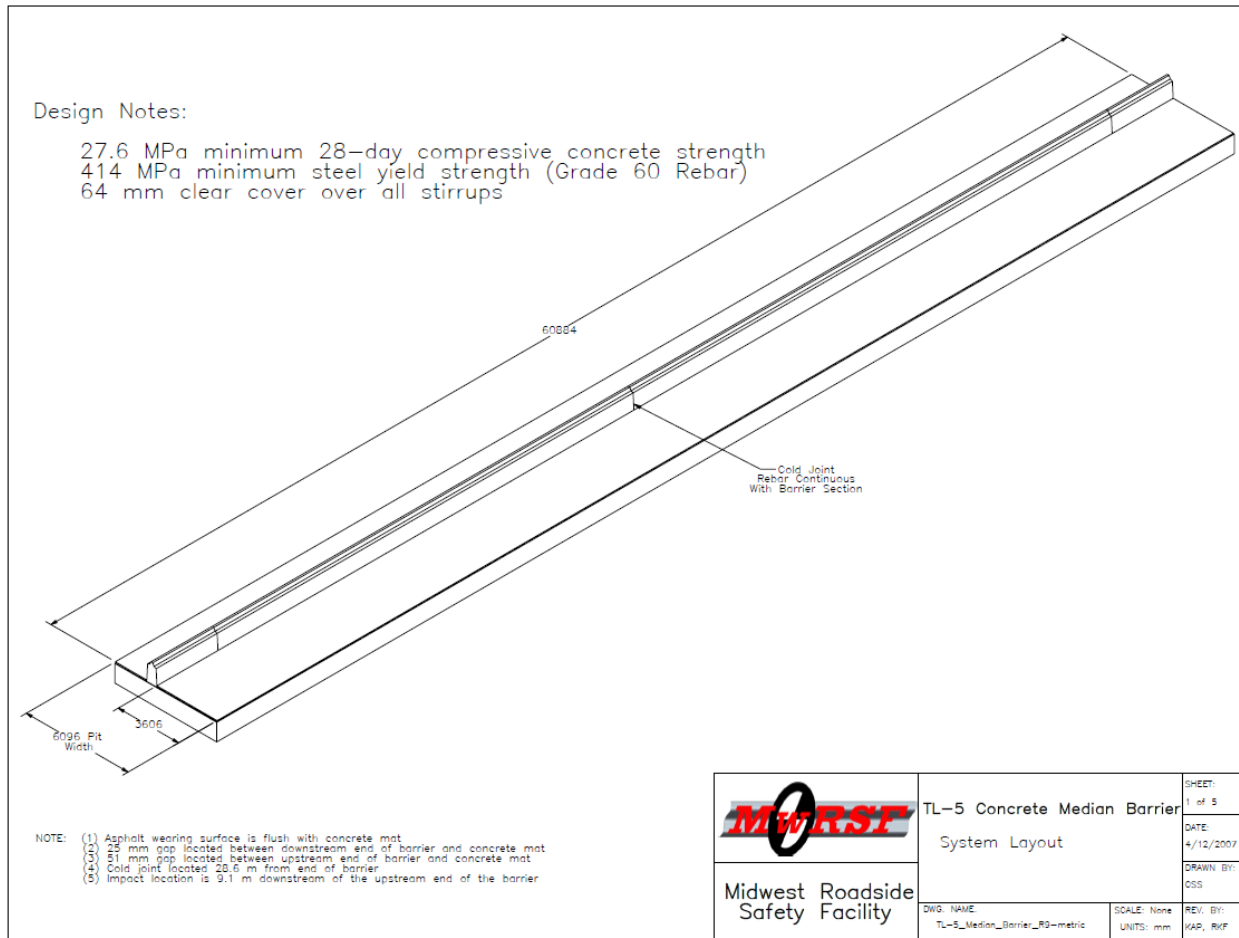**Figure 2. Test installation layout, Test No. MAN-1, reprinted from [15]**

Figure 3. Layout detail, Test No. MAN-1, reprinted from [15]

The FEA model developed in LS-DYNA in order to simulate the full-scale crash test is a single barrier segment with total length of 45.72 m (150 ft) and tests the capacity of the interior section of the Manitoba concrete bridge rail as opposed to test of the end section in the full-scale crash test [15]. 50 mm x 50 mm x 50 mm (2 in x 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 [11]. 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%

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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 [11]. MAT_CSCM_Concrete (MAT_159) was used to model the concrete [11]. 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 [11]. After running multiple simulations for parametric study, 9.45% effective plastic strain criterion was observed to develop concrete erosion comparable to the full-scale crash test. The cross section and layout of Manitoba concrete bridge rail FE model is shown in Figure 4.

3.2.2 Concrete Median Barrier

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) [16]. 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. 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 [16]. The full-scale crash test (TL5CMB-2) was performed with the tractor-van trailer impacting at a distance of 9.1 m (29.9 ft) from the upstream end of the barrier. The full-scale crash test installation layout and layout details for the Concrete Median barrier are shown in Figure 5 and Figure 6 [16].

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Figure 4. Cross-section and layout of Manitoba Concrete Bridge Rail FE model

Design Notes:

    27.6 MPa minimum 28-day compressive concrete strength
    414 MPa minimum steel yield strength (Grade 60 Rebar)
    64 mm clear cover over all stirrups

60884

Cold Joint
Rebar Continuous
With Barrier Section

6096 Pit
Width

3606

NOTE: (1) Asphalt wearing surface is flush with concrete mat
         (2) 25 mm gap located between downstream end of barrier and concrete mat
         (3) 51 mm gap located between upstream end of barrier and concrete mat
         (4) Cold joint located 28.6 m from end of barrier
         (5) Impact location is 9.1 m downstream of the upstream end of the barrier

MwRSF

Midwest Roadside
Safety Facility

TL-5 Concrete Median Barrier
System Layout

SHEET:
1 of 5

DATE:
4/12/2007

DRAWN BY:
OSS

DWG. NAME.
TL-5_Median_Barrier_R9-metric

SCALE: None
UNITS: mm

REV. BY:
KAP, RKF

Figure 5. Test installation layout, Test No. TL5CMB-2, reprinted from [16]

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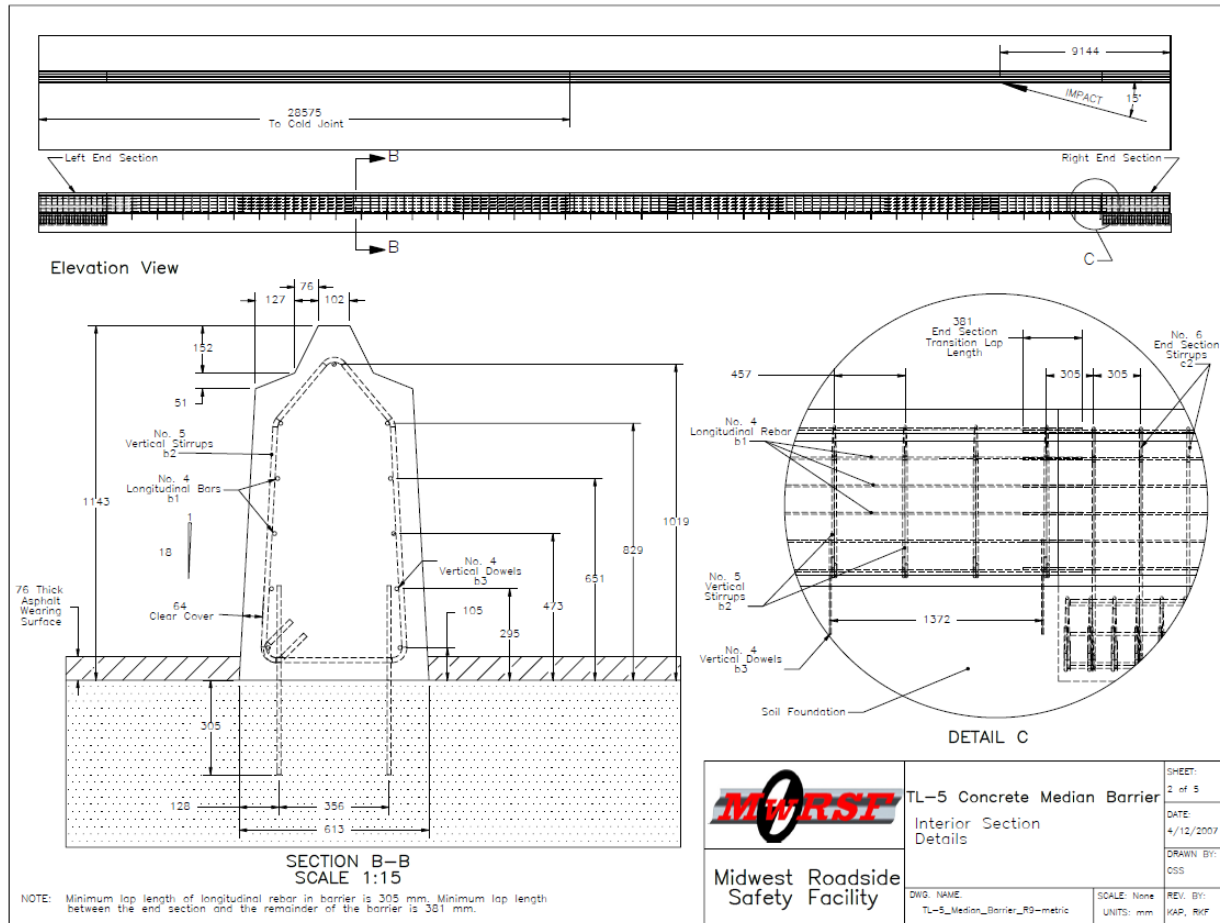
Figure 6. Layout detail, Test No. TL5CMB-2, reprinted from [16]

The FEA model developed in LS-DYNA in order to simulate the full-scale crash test is a single barrier segment with total length of 60.88 m (199.75 ft). 38 mm x 38 mm x 38 mm (1.5 in x 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 [11]. 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 the calculation after the plastic strain reaches this value.

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Constrained_Beam_In_Solid (CBIS) card was used to constrain the reinforcing steel in concrete [11]. MAT_CSCM_Concrete (MAT_159) was used to model the concrete [11]. 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 modeled 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 [11]. The concrete model was allowed to erode during the impact and MAT_Add_Erosion card was used to define the concrete erosion parameters [11]. After running multiple simulations for parametric study, 9.9% effective plastic strain criterion was observed to develop concrete erosion comparable to the TL5CMB-2 full-scale crash test. The cross section and layout of Concrete Median barrier FE model is shown in Figure 7.
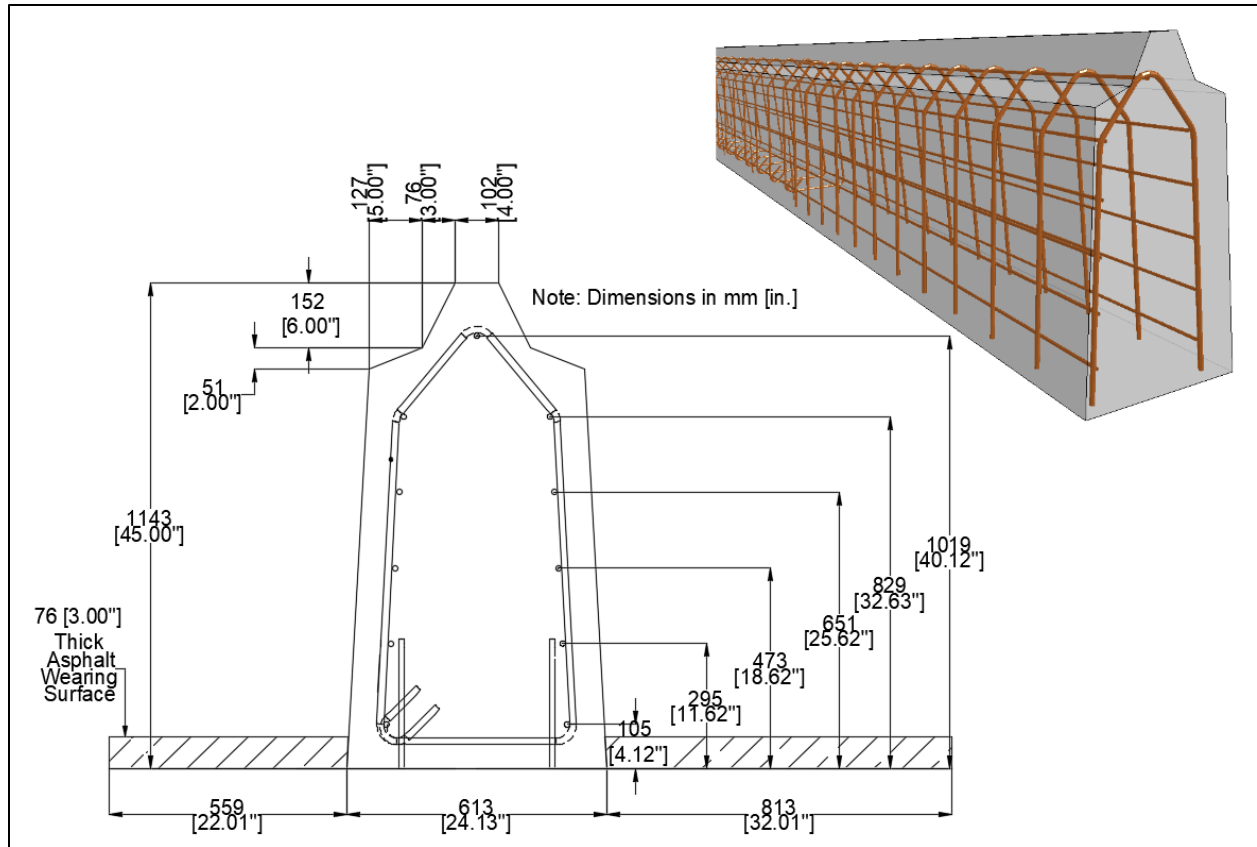
Figure 7. Cross-section and layout of Vertical Faced Concrete Median Barrier FE model

3.2.3 Tractor-Van Trailer

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 [15]. 1991 White GMC Conventional WG65T tractor with a 1988 Pines 14.6 m (48 ft) trailer was used to test the Concrete Median barrier [16].
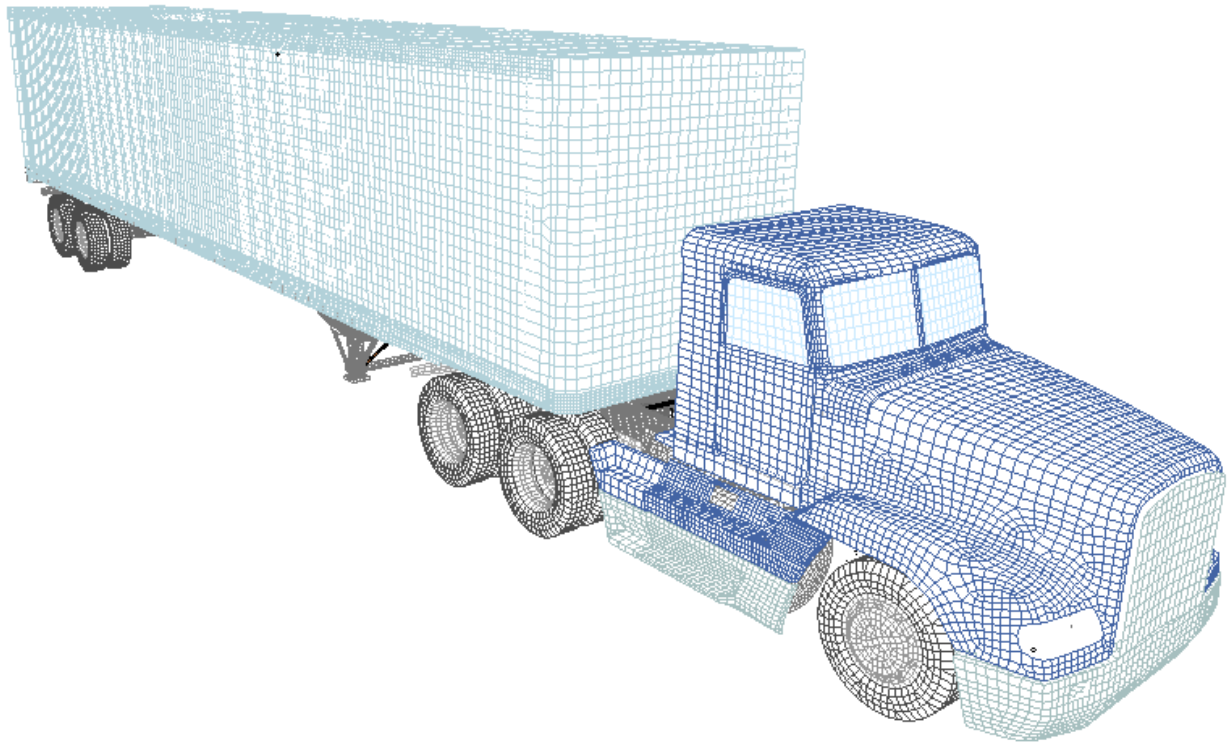
Figure 8. Existing FEA model of 36000V tractor-van trailer

An existing proprietary tractor-van trailer FEA model as shown in Figure 8 was used in the impact simulations involving both Manitoba concrete bridge rail and Concrete Median barrier. The FEA model was initially developed by National Crash Analysis Center (NCAC) and released by National Transportation Research Center, Inc. (NTRCI) [12, 13, 14]. 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 [11]. Element_Seatbelt_Accelerometer card was defined in the cabin as well as additional locations to collect acceleration data for occupant risk assessment and validation [11].

3.3 Validation

The leading truck impact simulation results were evaluated against the corresponding full-scale crash test results before running the following truck simulations.
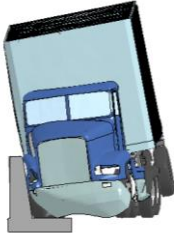
3.3.1 Manitoba Concrete Bridge Rail – Leading Tractor-Van Trailer Impact Simulation

3.3.1.1 Qualitative Evaluation
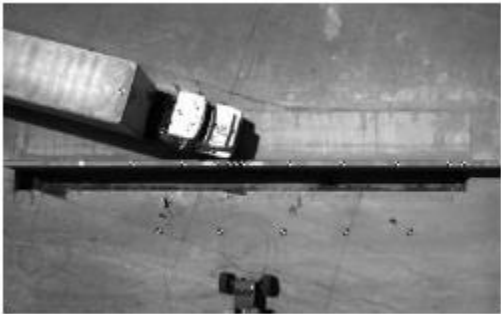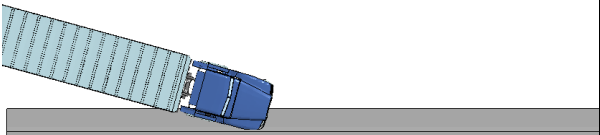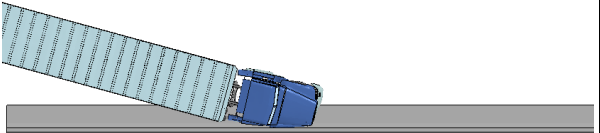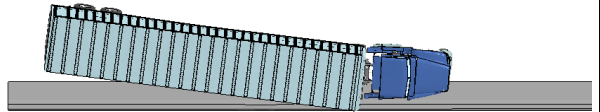
The sequential snapshots from the Manitoba concrete bridge rail leading truck impact simulation were compared against the full-scale crash test to make sure that the basic kinematic response and phenomenological events are in good agreement. Table 2 and Table 3 show the frame comparison from Test No. MAN-1 and the computer simulation starting at zero second, i.e. the time of first contact between tractor-van trailer and the barrier during impact event [15]. The basic kinematic response of the FEA vehicle was in good agreement with the full-scale crash test vehicle and the basic phenomenological events from the full-scale crash test were well replicated by the FEA.

Table 2. Frame Comparison of Full-Scale Crash Test MAN-1 and Computer Simulation – Front View, Adapted from [15]

Time (s)	Test No. MAN-1	Computer Simulation
0		
0.5		
1.0		
1.25		

Table 3. Frame Comparison of Full-Scale Crash Test MAN-1 and Computer Simulation – Top View, Adapted from [15]

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

25
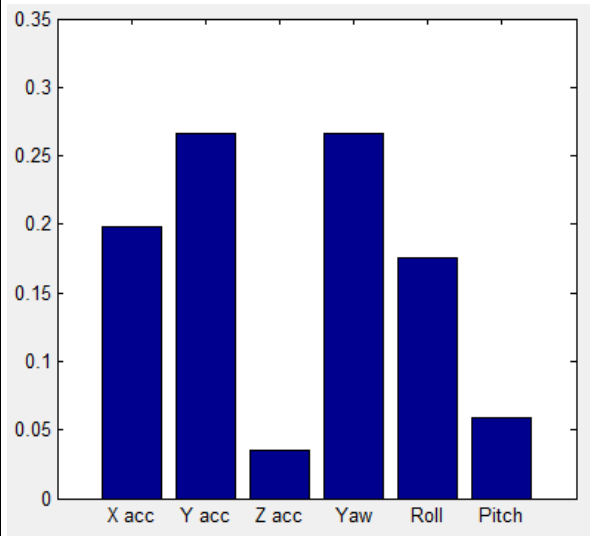
3.3.1.2 Quantitative Evaluation

The leading truck impact simulation was quantitatively evaluated against the full-scale crash test following the Roadside Safety Simulation Validation Program (RSVVP) guidelines [18, 19]. MwRSF provided the full-scale crash test data from DTS and SLICE2 accelerometer and rate sensor units [15]. DTS unit was located in the cab of the tractor while SLICE2 unit was mounted inside the trailer directly above front tandem axle as shown in Figure 9 [15]. Acceleration and angular displacement data were compared between the test and simulation according to Sprague and Geers (S&G) metrics and Analysis of 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 seconds 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 [18, 19]. Summary of quantitative multi-channel time history comparison of MAN-1 full-scale crash test data and FEA are shown in Table 4 and Table 5; the results were in marginal agreement.
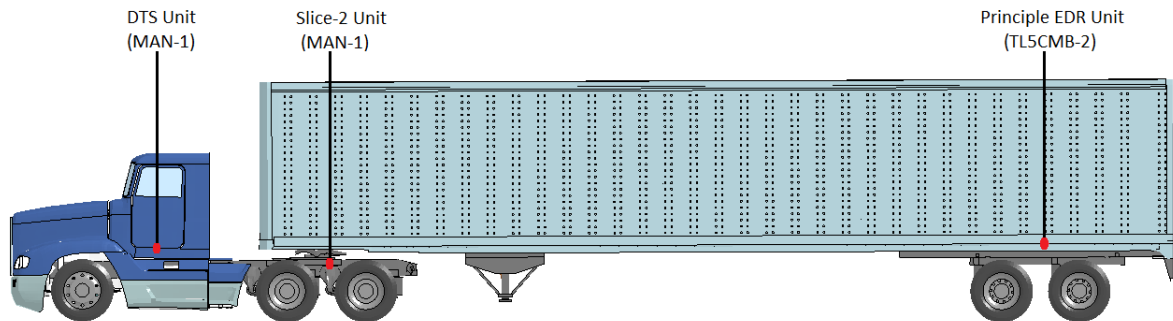
Figure 9. Accelerometer locations in tractor-van trailer FEA model

Table 4. Quantitative Multi-Channel Time History Comparison of Test vs FEA – DTS 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	P
		84.9*	32

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	Standard Deviation of Residuals

		-2.5	32.3

See footnote in Table 5.

Table 5. 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**

		M	P
O	***Sprauge-Geer Metrics*** Values less or equal to 40 are acceptable.		
		65*	**41.1***

		Mean Residual	Standard Deviation of Residuals
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 $(\bar{e} \le 0.05 \cdot a_{Peak})$ • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \le 0.35 \cdot a_{Peak}$)		
		-14.8*	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 S&G and ANOVA mean residual 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.

3.3.1.3 Occupant Risk

The occupant risk metrics for the leading tractor-van trailer impact simulation were calculated using Test Risk Assessment Program (TRAP) [17]. The data from the simulation was filtered in LS-DYNA using SAE 180 filter. TRAP calculates the components of Occupant Impact Velocity (OIV) and Occupant Ridedown Acceleration (ORA) as recommended by MASH; in addition, it also calculates Theoretical Head Impact Velocity (THIV), Post-Impact Head Deceleration (PID) and Acceleration Severity Index (ASI) as recommended by European Committee for Standardization (CEN) [17]. The occupant risk metrics for the full-scale crash test were obtained from the MwRSF report [15]. The assessment results from the full-scale crash test and FEA are shown in Table 6 [15, 18]. According to the results, the occupant risk factors for the full-scale crash test and FEA are comparable, and the differences are within the MASH recommended limits.

Table 6. Occupant Risk Comparison – Test vs FEA

Evaluation Criteria	Known Result	Analysis Result	Relative Diff.	Agree?
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
• Lateral OIV [m/s (ft/s)]	-4.92 (-16.14)	5.2 (17.06)	Abs. Val < 2 (6.56)	Yes
• THIV [m/s (ft/s)]	4.41 (14.47)	5.3 (17.39)	< 2 (6.56)	Yes
The relative difference in the Occupant Ridedown Accelerations is less than 20 percent or < 4g: • Longitudinal ORA	-4.04	-6.4	< 4g	Yes
• Lateral ORA	-6.3	-10.4	~ < 4g	**Border-line***
• PHD	6.52	10.5	< 4g	Yes
• ASI (DTS Unit)	0.67	0.73	9%	Yes

* 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.

3.3.1.4 Barrier Damage

The damage at the impact location in the full-scale crash test MAN-1 and leading truck impact simulation are shown in Figure 8 [15]. Manitoba concrete bridge rail damage in the full-scale crash test was minimum and consisted of contact marks, gouging, spalling and minor cracking [15]. Concrete spalling with maximum depth of 52 mm (2 in) was observed beginning at the downstream end of the joint cap, i.e.11.85 m (38.9 ft.) from the upstream end of the barrier setup and extended about 1 m (37 in.) downstream [15]. The erosion at the top of the bridge rail in the leading tractor-van trailer impact simulation was comparable to the erosion in the full-scale crash test even though the former tested the internal section while the later tested the end section. This was as expected as the end section design in the full-scale crash test was modified to match the capacity of the internal section. Erosion at the top of the barrier in the impact simulation began at about 13194 mm (43.3 ft) from the upstream end and extended about 747 mm (2.5 ft).

(a)   (b)
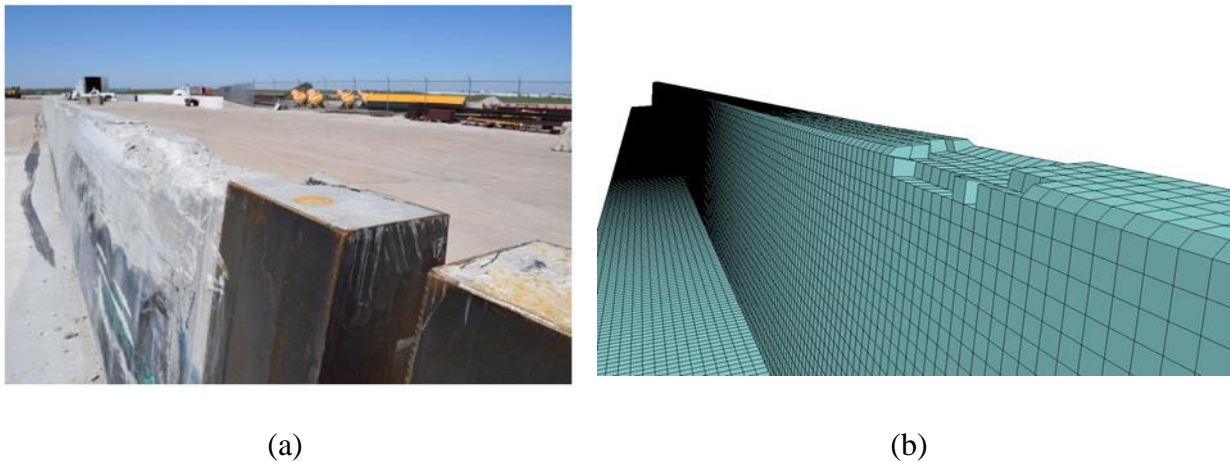
Figure 10. Manitoba Concrete Bridge Rail damage, (a) MAN-1 crash test, (b) impact simulation, adapted from [15]
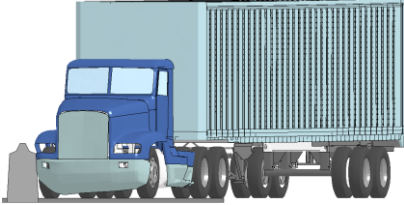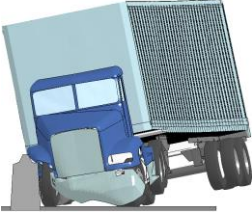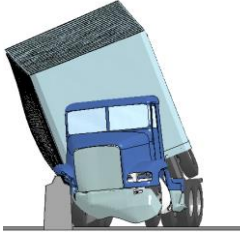
3.3.2 Concrete Median Barrier – Leading Tractor-Van Trailer Impact Simulation

3.3.2.1 Qualitative Evaluation
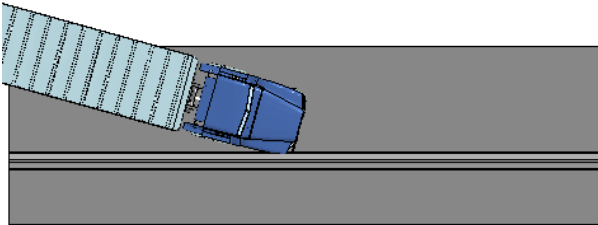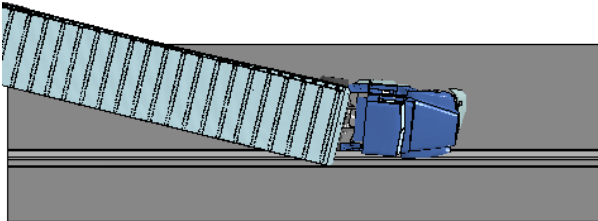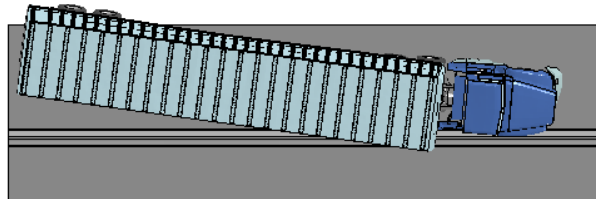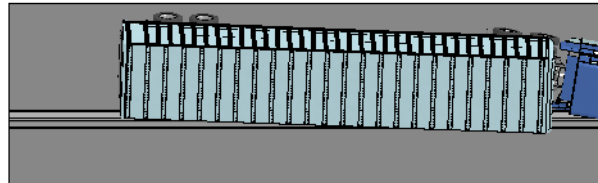
The sequential snapshots from the Concrete Median barrier leading truck impact simulation were compared against the full-scale crash test to make sure that the basic kinematic response and phenomenological events are in good agreement. Table 7 and Table 8 show the frame comparison from Test No. TL5CMB-2 and the computer simulation starting at zero second, i.e. the time of first contact between tractor-trailer and the barrier during impact event [16]. The basic kinematic response of the FEA vehicle was in good agreement with the full-scale crash test vehicle and the basic phenomenological events from the full-scale crash test were well replicated by the FEA.

Table 7. Frame Comparison of Full-Scale Crash Test TL5CMB-2 and Computer Simulation – Front View, Adapted from [16]

Time (s)	Test No. TL5CMB-2	Computer Simulation
0		
0.4		
0.78		
1.16		
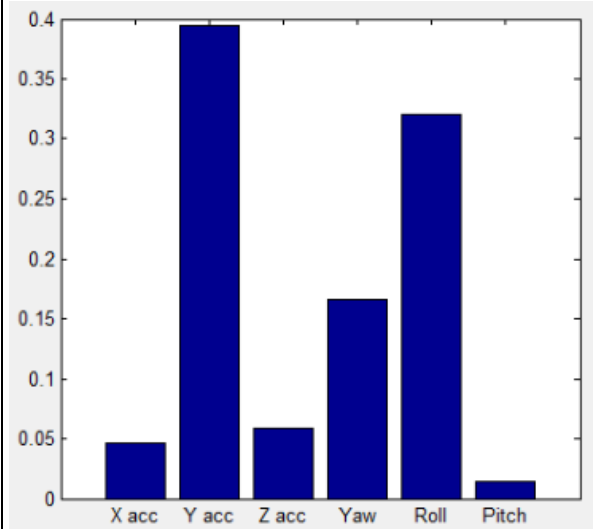
Table 8. Frame Comparison of Full-Scale Crash Test TL5CMB-2 and Computer Simulation – Top View, Adapted from [16]

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

3.3.2.2 Quantitative Evaluation

The leading truck impact simulation was quantitatively evaluated against the full-scale crash test following the RSVVP guidelines [18, 19]. The full-scale crash test data from principle EDR accelerometer and rate sensor units was provided by MwRSF, the unit was mounted near the tractor tandem axles as shown in Figure 9 above [16]. The secondary EDR unit mounted near the tractor tandem axles did not record any data due to technical issues [16]. Acceleration and angular displacement data were compared between the test and simulation according to S&G metrics and 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 seconds 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 [18, 19]. Summary of quantitative multi-channel time history comparison of TL5CMB-2 test data and FEA are shown in Table 9. The results were in good agreement even though the mean residual ANOVA metric was considered borderline.

Table 9. Quantitative Multi-Channel Time History Comparison of Test vs FEA – Principle EDR Unit

Evaluation Criteria (time interval [0 sec; 1.77 sec])		
Channels (Select which was used)		
☒ X Acceleration	☒ Y Acceleration	☒ Z Acceleration
☒ Roll rate	☒ Pitch rate	☒ Yaw rate

		Channel Weight Factors
Multi-Channel Weighting Method	☐ Peaks ☐ Area I ☒ Area II ☐ Inertial	

O	**Sprauge-Geer Metrics** Values less or equal to 40 are acceptable.	M	P
		39.7	27.1

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	Standard Deviation of Residuals
		-5.8*	15.1

* According to the results, the FEA model was in good 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.

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3.3.2.3 Occupant Risk

As the secondary EDR unit mounted near the tractor tandem axles did not record any data due to technical issues, the researchers were not able to perform occupant risk assessment for the full-scale crash test TL5CMB2 [16]. So, the comparison of occupant risk metrics between the full-scale crash test and the leading tractor-van trailer impact simulation could not be made.

3.3.2.4 Barrier Damage

The damage at the impact location in the full-scale crash test TL5CMB-2 and leading truck impact simulation are shown in Figure 11 [16]. Minimal damage occurred to the Concrete Median barrier in the full-scale crash test and consisted of contact marks, gouging, spalling and cracking [16]. The top protrusion saw a lot of contact marks, gouging and occasional spalling as the trailer rode down it during impact. Concrete spalling was maximum at top front edge between 12.8 m (42 ft) and 14 m (46 ft) from the upstream end of the barrier setup; the gouging and spalling at the location was about 76 mm (3 in) to 102 mm (4 in) wide [16]. The erosion at the top of the barrier in the leading tractor-van trailer impact simulation was comparable to the erosion in the full-scale crash test; erosion occurred at the top of the FEA model protrusion beginning at about 12500 mm (41 ft.) and extended downstream for about 870 mm (2.85 ft.).

<div align="center">(a)   (b)</div>
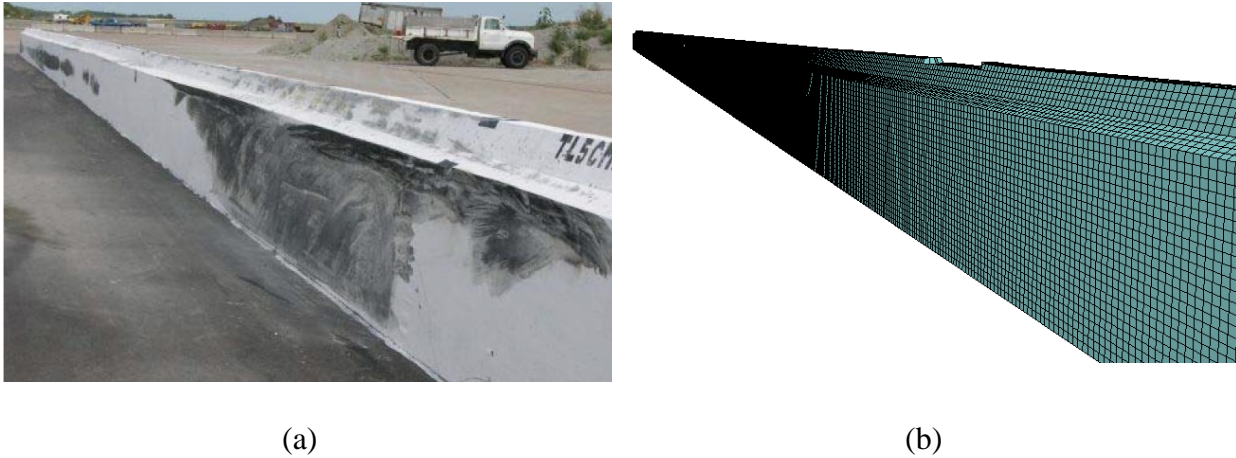
Figure 11. Concrete Median Barrier damage, (a) TL5CMB-2 Crash Test, (b) impact Simulation, adapted from [16]

3.3.3 Model Validity

While the quantitative evaluation of Concrete Median barrier showed good agreement between the full-scale crash test and impact simulation, the quantitative evaluation results of Manitoba concrete bridge rail were only in marginal agreement with the default requirements. The tractor-van trailer and the simulations were deemed acceptable based on overall evaluation results discussed in Subsections 3.3.1 and 3.3.2.

4. FEA RESULTS[*]

4.1 Manitoba Concrete Bridge Rail FEA Results

This section discusses the results of the finite element simulation for the five consecutive

MASH TL5 impacts into Manitoba concrete bridge rail modeled with 1302 mm (4.3 ft) of bridge

deck width.

4.1.1 Barrier Performance

Table 10. Barrier Performance - Manitoba Concrete Bridge Rail with Deck

	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

---

[*] Part of the data reported in this section is reprinted from "Evaluation of the Injury Risks of Truck Occupants Involved in a Crash as a Result of Errant Truck Platoons" by Jin, H., Sharma, R., Meng, Y., Untaroiu, A., Dobrovolny, C.S., and Untaroiu, C., 2018. 15th International LS-DYNA Users Conference, pp. 1-16.

The Manitoba concrete bridge rail was impacted consecutively by five tractor-van trailers at an angle of 15.2 degrees and speed of 83.2 km/h (51.7 mph) about 10516 mm (34.5 ft) from the upstream end of the barrier. The barrier performance for each impact is summarized in Table 10 and Figure 11 [15]. It was observed that all of the impacting vehicles were successfully contained and redirected by the barrier. The tractor-van trailers in first and second impact came to final configuration, i.e. tires on both left and right sides came back in contact with the ground, about 1.25 seconds after initial contact. Third, fourth and fifth tractor-van trailers reached the final configuration at about 1.4 seconds, 1.42 seconds and 1.54 seconds after initial contact.
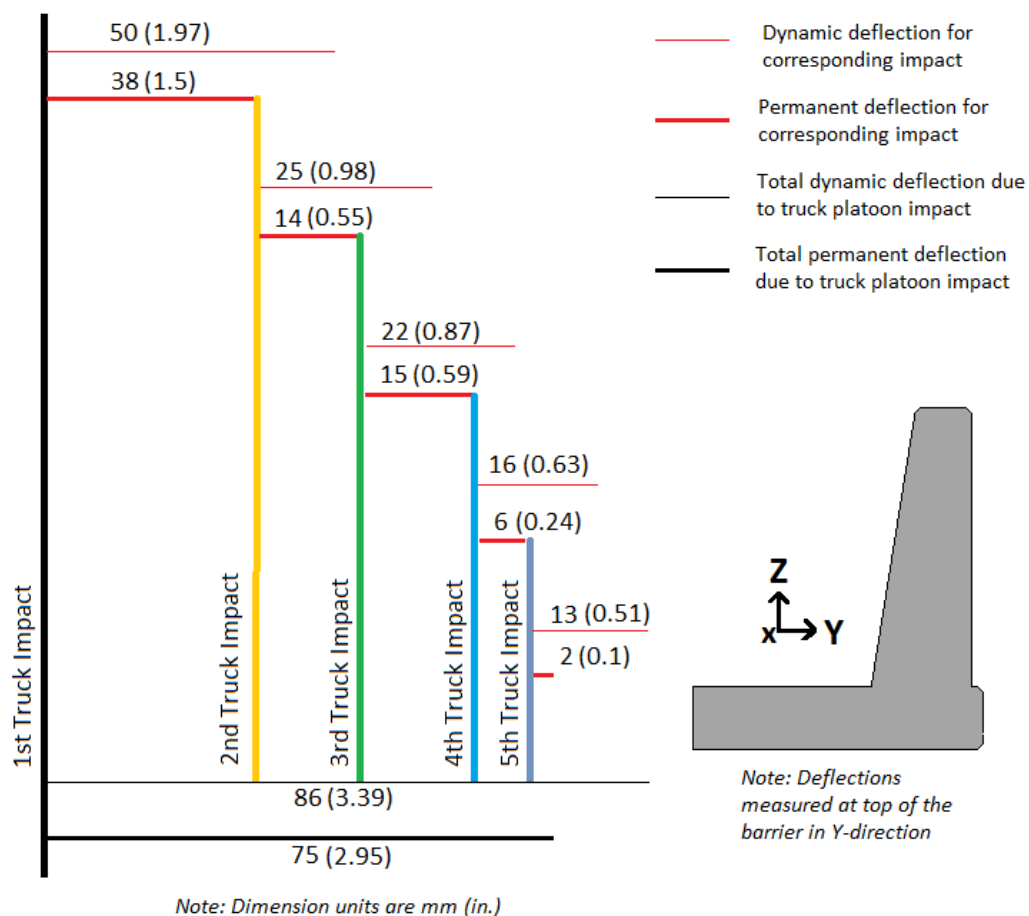
Figure 12. Manitoba Concrete Bridge Rail deflection due to truck platoon impact

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4.1.2 Energy Values

Tractor-van trailer impacting against the bridge rail 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 GLSTAT energies from LS-DYNA reported in this section include the contribution of eroded elements during the impact [20]. 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 remains close to 100% during the impact period for first through fifth tractor-van trailer impacts into the Manitoba concrete bridge rail. It is recommended that the total energy of the system should not vary more than 10% from the beginning to end of the run [18]. Figure 13 and Figure 14 show the energy distribution for first and fifth tractor-van 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 50% to 60%; this energy is due to the remaining velocity of the impacting truck.
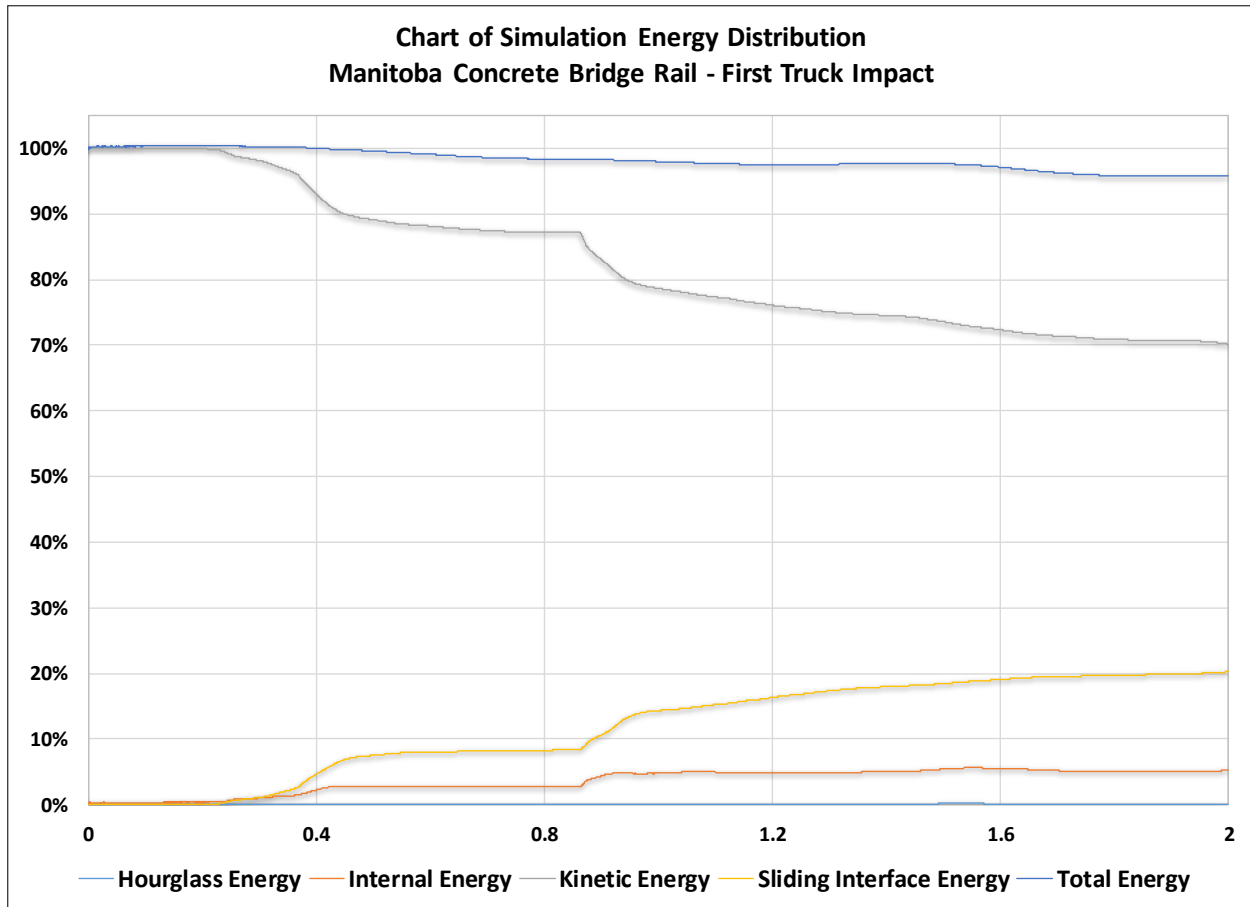
Figure 13. Energy distribution time history – first truck impact into Manitoba Concrete Bridge Rail
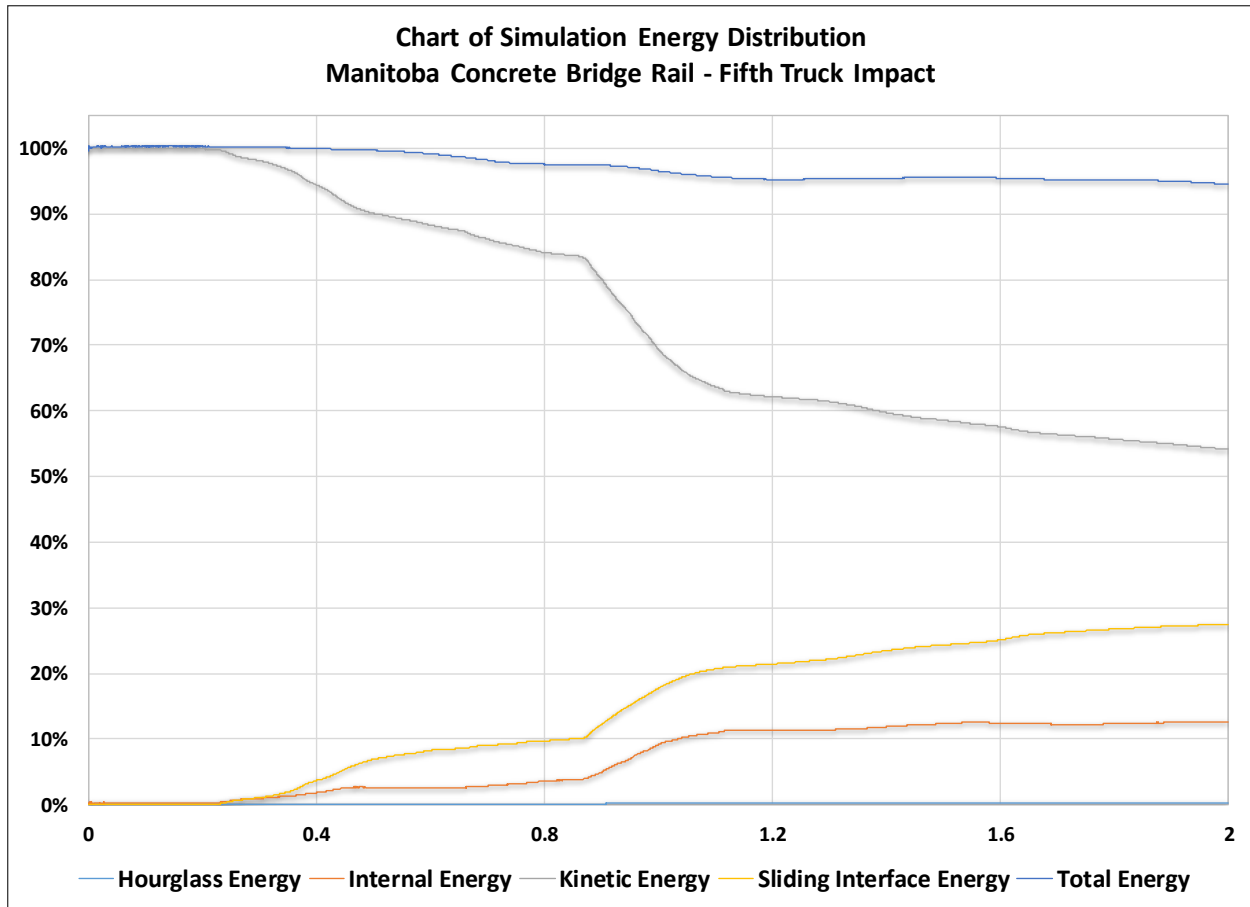
Figure 14. Energy distribution time history – fifth truck impact into Manitoba Concrete Bridge Rail
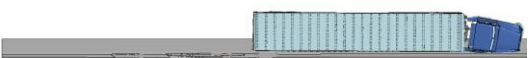
4.1.3 Vehicle Stability

Table 11 and Table 12 show the frame comparison for the truck platoon impact into Manitoba concrete bridge rail. Due to higher angular displacements during impact, it was observed that the tractor-van trailers in third through fifth impacts took longer time to stabilize as compared to the first or second impact.

**Table 11. Frame Comparison of Impact Simulations for Manitoba Concrete Bridge Rail –
Front View**

Time (s)	0	0.5	1	1.25
1st Impact				
2nd Impact				
3rd Impact				
4th Impact				
5th Impact				
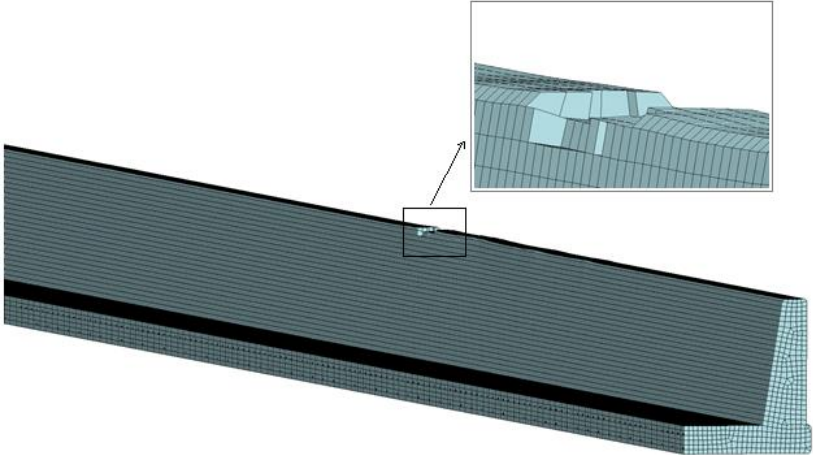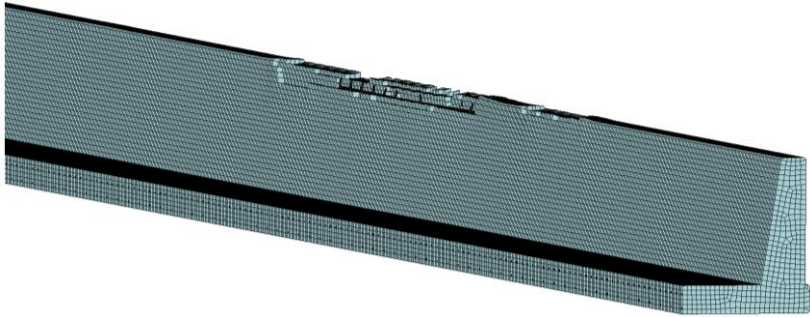
Table 12. Frame Comparison of Impact Simulations for Manitoba Concrete Bridge Rail – Top View

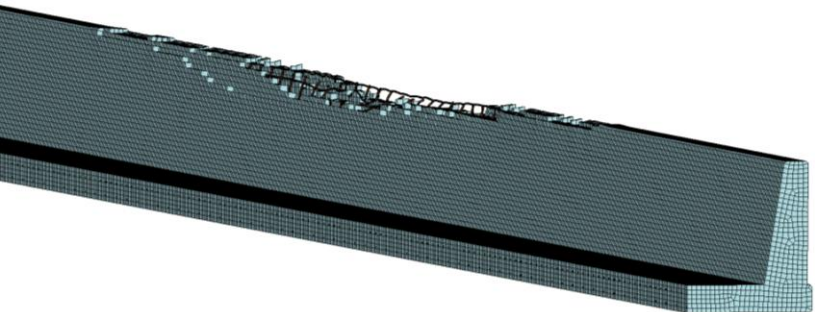| Time (s)	0	0.5
1st Impact		
2nd Impact		
3rd Impact		
4th Impact		
5th Impact		
Time (s)	**1**	**1.25**
1st Impact		
2nd Impact		
3rd Impact		
4th Impact		
5th Impact		

44
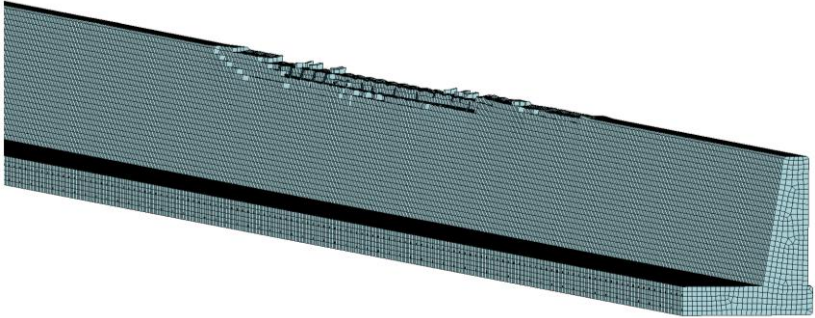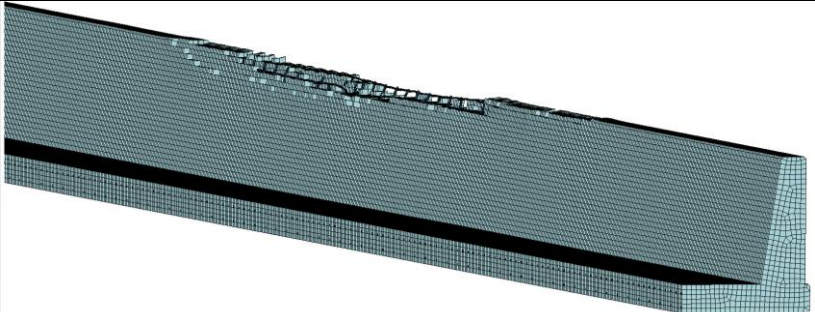
4.1.4 Barrier Strength

Concrete erosion and steel damage at the top of the Manitoba concrete bridge rail due to five consecutive tractor-van trailer impacts can be observed in Table 13. Erosion parameter for the concrete was defined such that the elements are deleted when the effective plastic strain in the concrete exceeds 9.45%. Table 14 shows the concrete effective plastic strain in impact side and back side of the bridge rail respectively for the impacts. Cracks are likely to occur at the area shown in red where the strain values are the highest. Table 15 shows and discusses the plastic strains in the steel reinforcement of the barrier at the end of each impact. The steel reinforcement modeled as beam elements is not considered in the calculations if the maximum plastic strain exceeds 20%. Reinforcement in navy blue represents negligible or no plastic strain. 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.

Table 13. Erosion of Manitoba Concrete Bridge Rail - Five Consecutive Impact Simulations

1ˢᵗ Impact	
	Erosion occurred at the top of the barrier beginning at about 13194 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 back side of the barrier was eroded at the described location. A line second-to-top layer of elements also eroded on the front side.
2ⁿᵈ Impact	
	Erosion occurred at a new location at the top of the barrier beginning at about 7648 mm (25.1 ft.) from upstream end and extended downstream for about 2246 mm (7.4 ft.). Existing eroded area from first impact grew and now began about 11445 mm (37.5 ft.) from the upstream end and was now about 7644 mm (25 ft.) long. About 13 lateral rebar's top ends and about 5100 mm (16.73 ft.) of the top two longitudinal rebar were exposed as a result of this impact.

Table 13 Continued

3rd Impact	
	Additional erosion occurred at the top of the barrier which now began at about 7501 mm (24.6 ft.) from the upstream end of the barrier and extended downstream for about 13486 mm (44.2 ft.). At the front face of the barrier where maximum damage was observed, which stretched over a span of 7590 mm (24.9 ft.), about five top layers of 50 mm solid elements were eroded and about 20 lateral rebar's top ends were exposed and damaged. Maximum of two top layers of solid elements were eroded on the back face of the barrier. .
4th Impact	
	Additional erosion occurred at the top of the barrier which now began at about 7198 mm (23.6 ft.) from the upstream end of the barrier and extended downstream for about 15638 mm (51.3 ft.). At the front face of the barrier where maximum damage was observed, which stretched over a span of 9391 mm (30.8 ft.), up to seven top layers of 50 mm solid elements were eroded and about 24 lateral rebar's top ends were exposed and damaged. Maximum of five top layers of solid elements were eroded on the back face of the barrier. .
5th Impact	
	Additional erosion occurred at the top of the barrier which still began at about 7198 mm (23.6 ft.) from the upstream end of the barrier but extended downstream for about 19236 mm (63.1 ft.). At the front face of the barrier where maximum damage was observed, which stretched over a span of 10090 mm (33.1 ft.), up to nine top layers of 50 mm solid elements were eroded and about 26 lateral rebar's top ends were exposed and damaged. Maximum of seven top layers of solid elements were eroded on the back face of the barrier. .

Table 14. Concrete Effective Plastic Strain of Manitoba Concrete Bridge Rail - Five Consecutive Impact Simulations
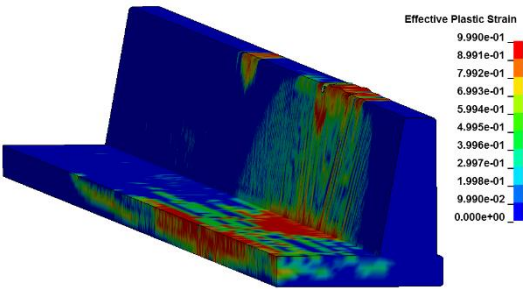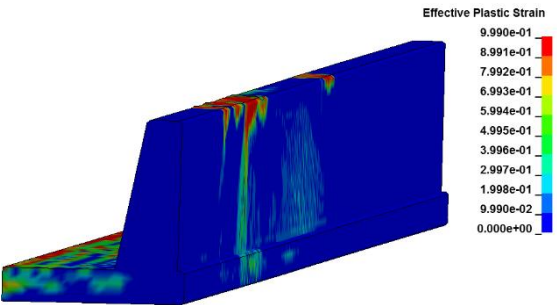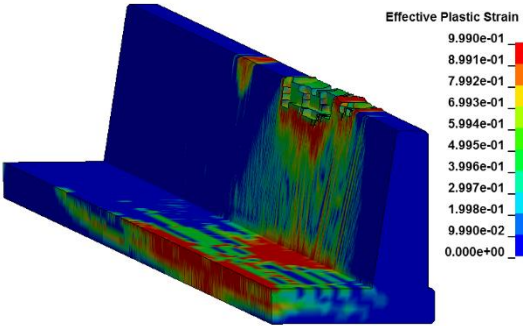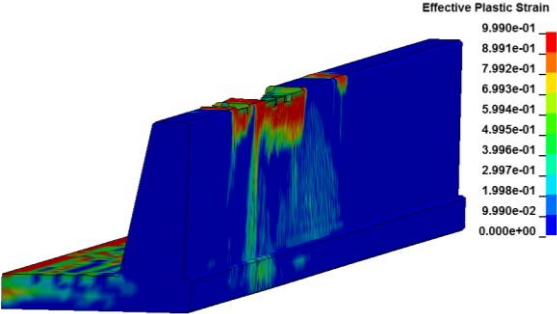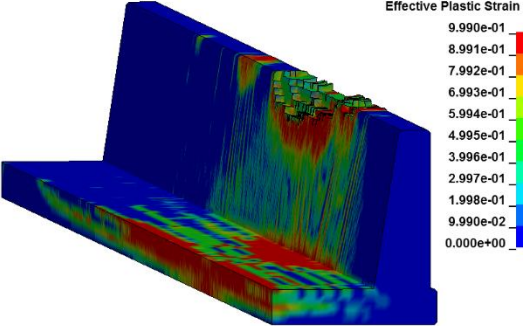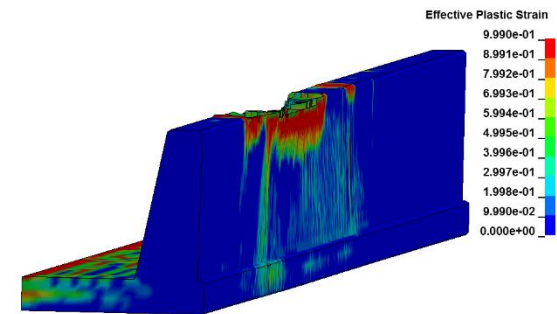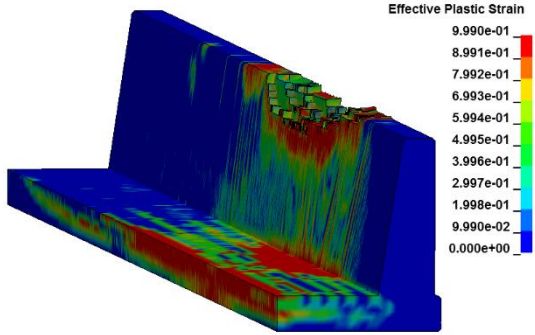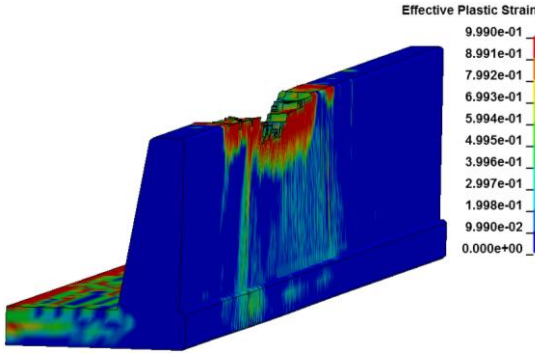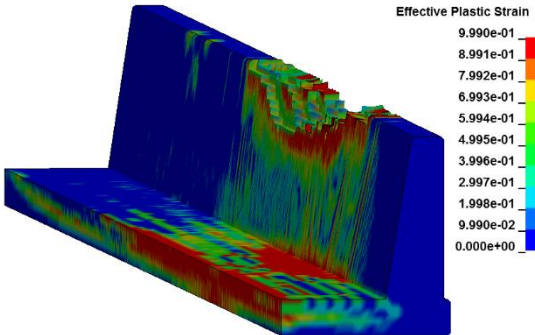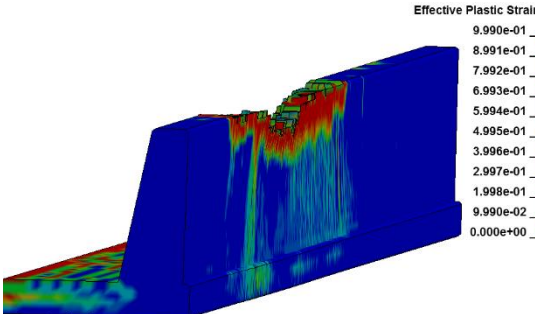
Truck No.	Concrete Effective Plastic Strain – Impact Side	Concrete Effective Plastic Strain –Back Side
1st		
2nd		
3rd		

Table 14 Continued

Truck No.	Concrete Effective Plastic Strain – Impact Side	Concrete Effective Plastic Strain –Back Side
4th		
5th		

Table 15. Steel Plastic Strain of Manitoba Concrete Bridge Rail - Five Consecutive Impact Simulations
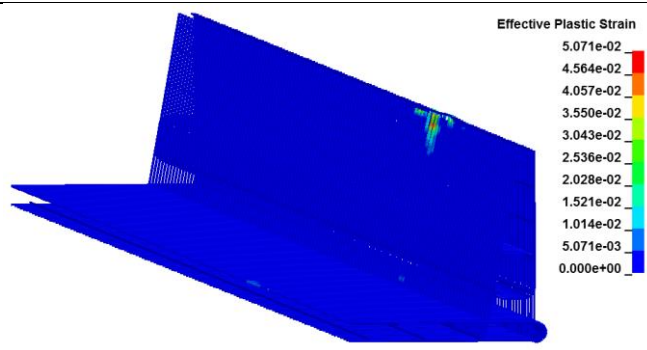
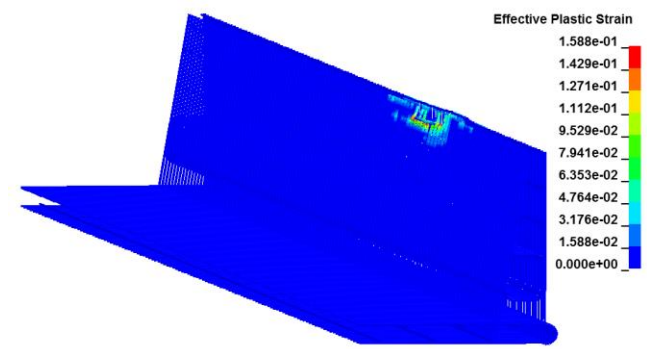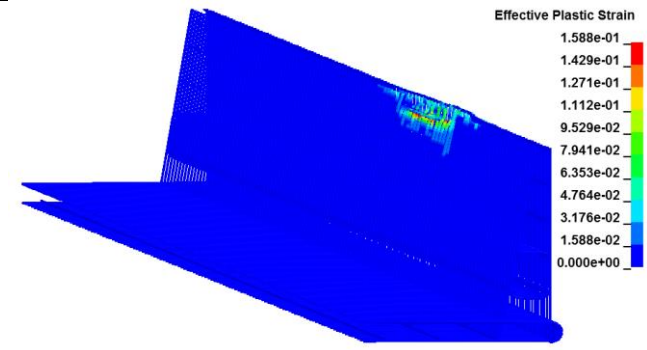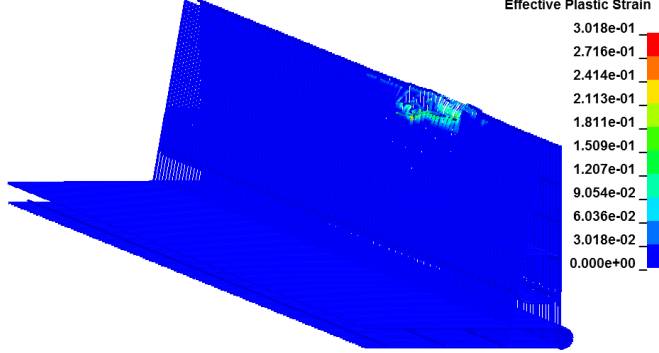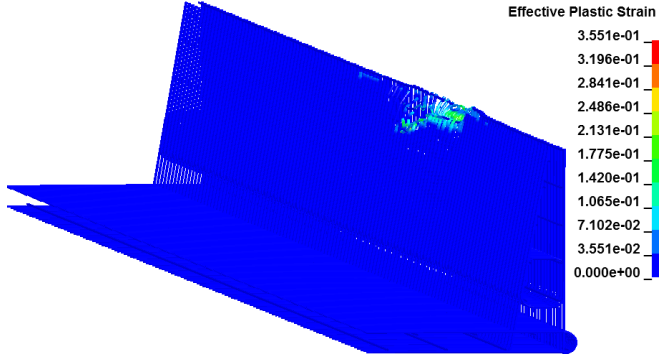|	Plastic Strain
1st Impact	
	The maximum plastic strain of about 5% is in traverse rebar in a small region at the top of the barrier. Most of the reinforcement has negligible or no plastic strain.
2nd Impact	
	At the region of impact, about three to four elements at the top-front end of about eight traverse rebar failed based on 20% maximum plastic strain criteria, those elements were not considered in further calculations. The maximum plastic strain for the rest of the reinforcement is about 16% which is present at the same region where the element failures occurred. The longitudinal rebar at the top-front end experienced plastic strain of up to 10%.
3rd Impact	
	At the region of impact, about three to four elements at the top-front end of twelve traverse rebar failed based on 20% maximum plastic strain criteria, those elements were not considered in further calculations. The maximum plastic strain for the rest of the reinforcement is about 16% which is present at the same region where the element failure occurred. At least 7491 mm (24.6 ft.) segments of two longitudinal rebar at the top-front end of the rebar were fully exposed due to concrete erosion.

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Table 15 Continued

.	Plastic Strain
4th Impact	
	At the region of impact, about three to seven elements at the top-front end of about sixteen traverse rebar failed based on 20% maximum plastic strain criteria, those elements were not considered in further calculations. The top-back ends of those rebar also experienced plastic strain of up to 19%. The maximum plastic strain for the rest of the reinforcement is right below 20% which is present at the same region where the element failures occurred. At least 8392 mm (27.5 ft.) segments of two longitudinal rebar at the top-front end of the rebar were damaged or fully exposed due to concrete erosion.
5th Impact	
	At the region of impact, about three to twelve elements at the top-front end of about twenty traverse rebar failed based on 20% maximum plastic strain criteria, those elements were not considered in further calculations. The top-back ends of those rebar also experienced plastic strain of more than 20%. At least 8843 mm (29 ft.) segments of two longitudinal rebar at the top-front end of the rebar were damaged or fully exposed due to concrete erosion.

4.1.5 Occupant Risk

The summary of occupant risk assessment and angular displacement for the five consecutive tractor-van trailer impacts into Manitoba concrete bridge rail are shown in Table 16. Occupant risk assessment was performed based on applicable safety evaluation criteria defined in MASH using TRAP program [1, 17]. The tractor-van trailer models stayed upright and rollover

did not occur during the simulated impact events. The impact velocities and ridedown accelerations observed in the impacts are below the MASH recommended limits [1].

Table 16. 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)] x-direction y-direction	9.1 (30) 12.2 (40)	0.37 (1.2) -1.58 (-5.2)	0.40 (1.3) -1.55 (-5.1)	0.4 (1.3) -1.55 (-5.1)	0.4 (1.3) -1.58 (-5.2)	0.43 (1.4) -1.52 (-5.0)
Ridedown Acc. (g's) x-direction y-direction	15 20	-6.4 10.4	-6.6 12.5	-6.1 13.9	-6.5 10.2	-6.5 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

4.2 Concrete Median Barrier FEA Results

This section discusses the results of the finite element simulation for the four consecutive MASH TL5 impact into Concrete Median barrier.

4.2.1 Barrier Performance

The barrier was impacted consecutively by four tractor-van trailers at an angle of 15.4 degrees and speed of 84.9 km/h (52.7 mph) about 9100 mm (30 ft) from the upstream end of the barrier. The barrier performance for each impact is summarized in Table 17 and Figure 15 [16]. It was observed that the impacting vehicles were successfully contained and redirected by the barrier. The tractor-van trailers in first and second impact came to final configuration, i.e. tires on both left and right sides came back in contact with the ground, 1.68 seconds after initial contact. Third and

fourth tractor-van trailers reached final configuration at about 1.72 seconds and 1.88 seconds after initial contact.

Table 17. Barrier Performance – Concrete Median Barrier

|	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
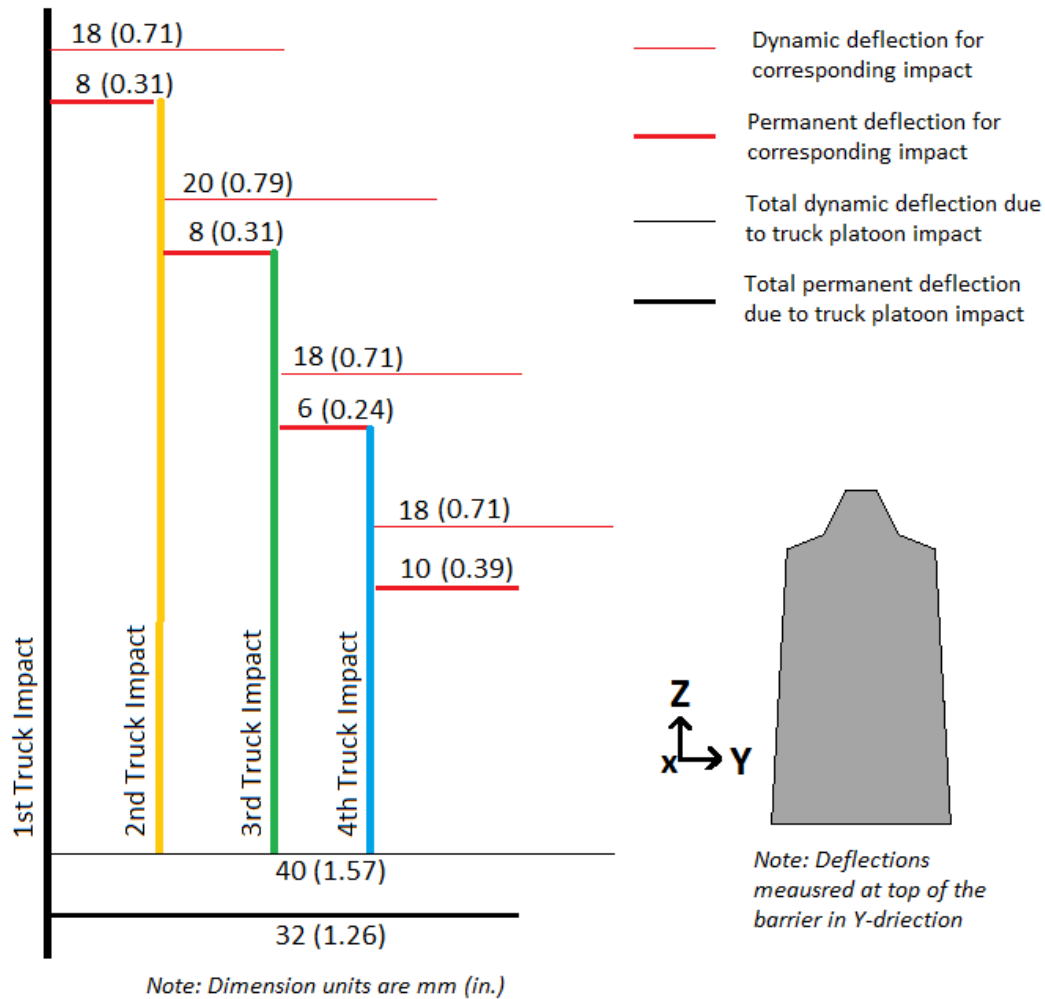
Figure 15. Concrete Median Barrier deflection due to truck platoon impact

4.2.2 Energy Values

As stated earlier, tractor-van trailer impacting against the bridge rail is a closed system and the total energy of the system is conserved. 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 remains close to 100% during the impact period for first through fourth tractor-van trailer impacts into the Concrete Median barrier. It is recommended that the total energy of the system should not vary more than 10% from the

beginning to end of the run [18]. Figure 16 and Figure 17 show the energy distribution for first and fourth tractor-van trailer impact simulation 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.
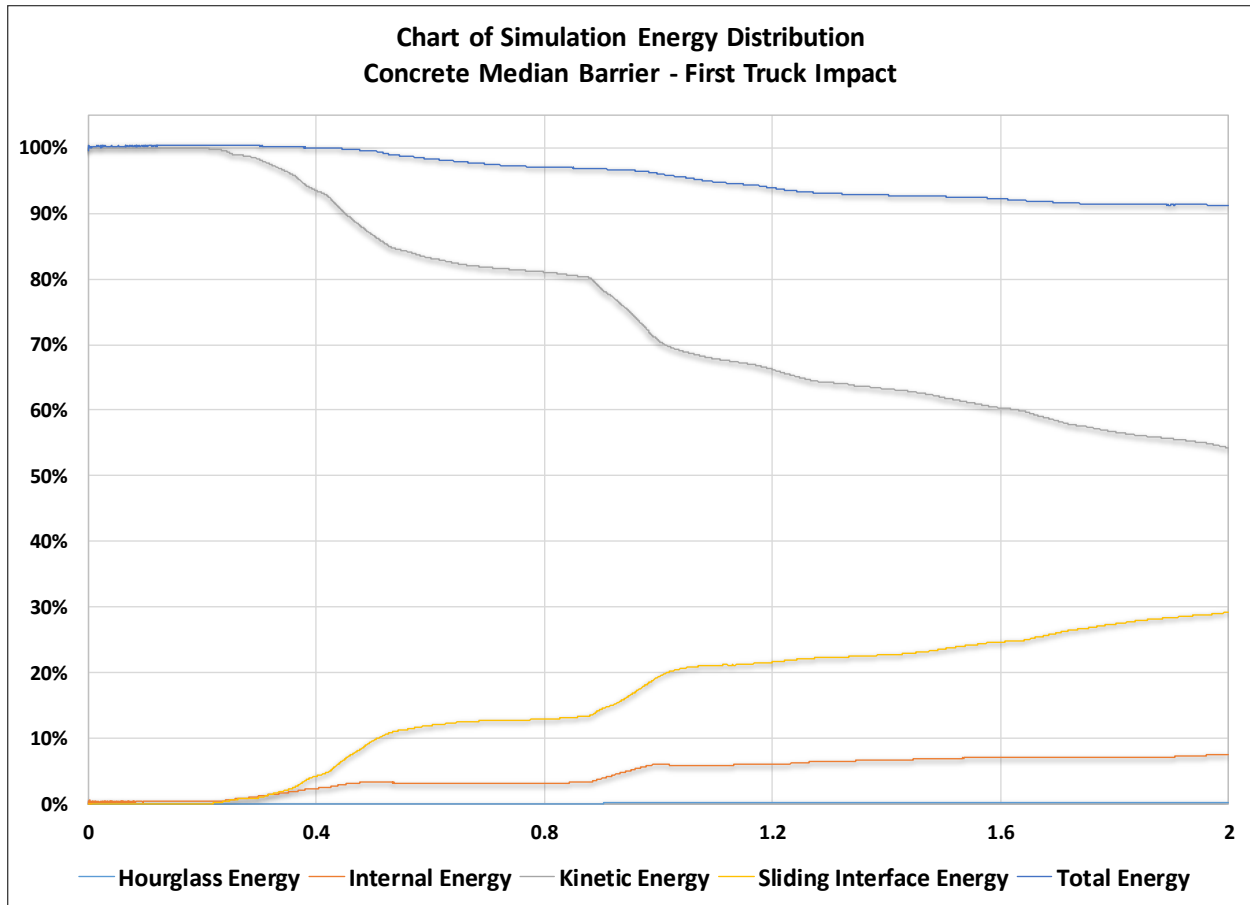
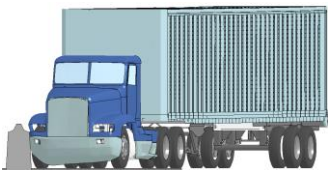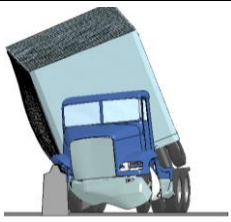**Figure 16. Energy distribution time history – first truck impact into Concrete Median Barrier**
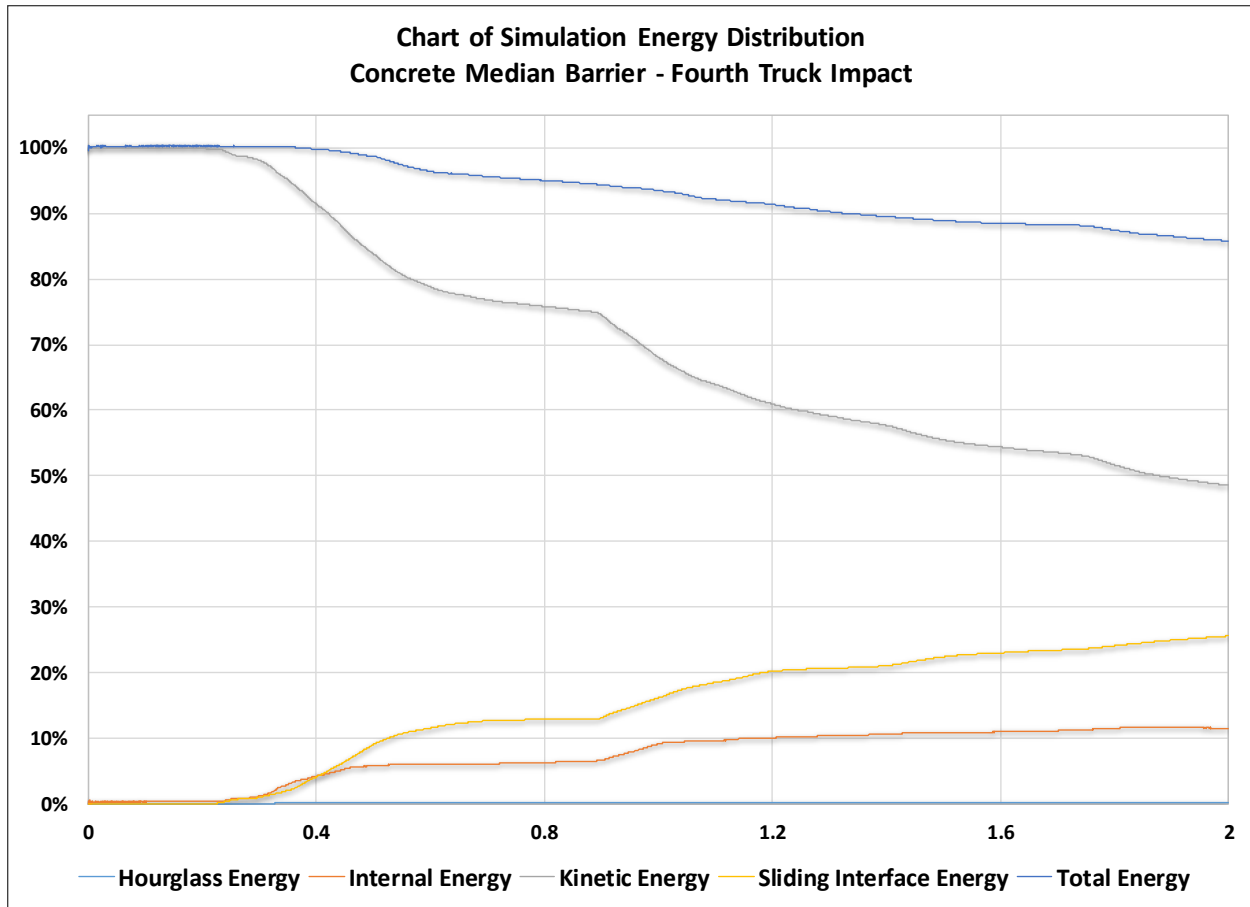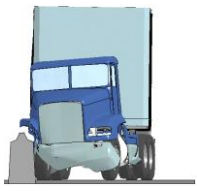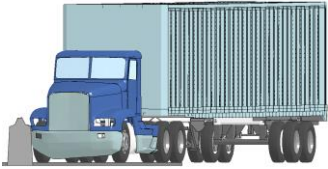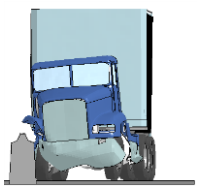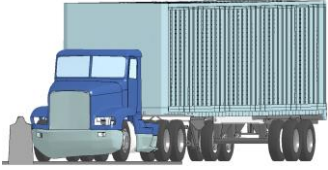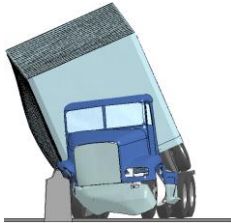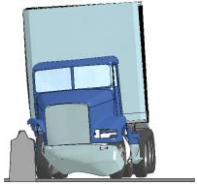
Figure 17. Energy distribution time history – fourth truck impact into Concrete Median Barrier
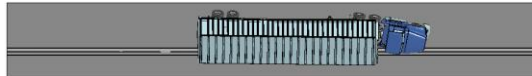
4.2.3 Vehicle Stability

Table 18 and Table 19 show the frame comparison for the truck platoon impact into Concrete Median barrier. Due to higher angular displacements during impact, it was observed that the tractor-van trailers in third and fourth impacts took longer time to stabilize as compared to the first or second impact.

Table 18. Frame Comparison of Impact Simulations for Concrete Median Barrier – Front View

Time (s)	0	0.78	1.16	1.68
1st Impact				
2nd Impact				
3rd Impact				
4th Impact				

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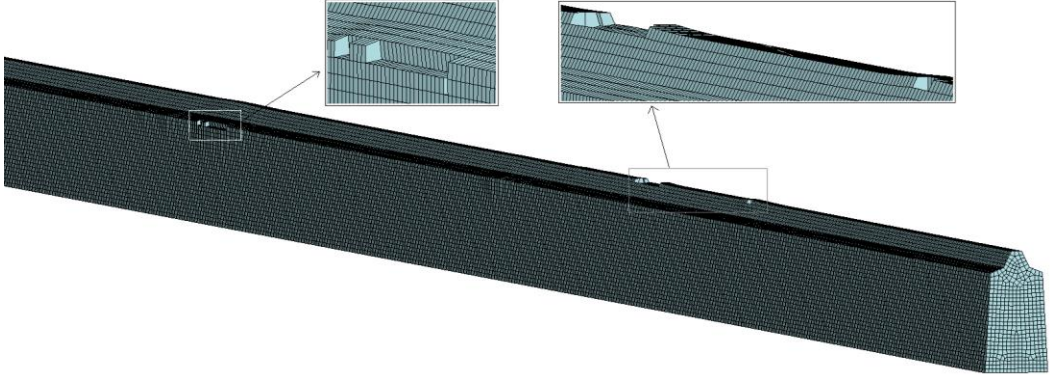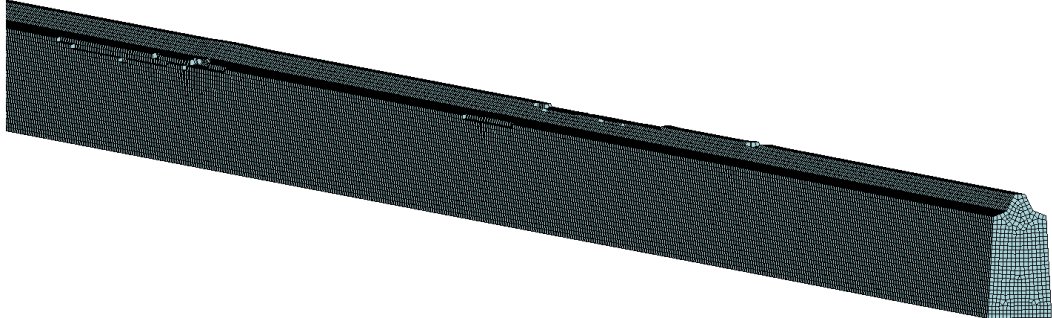
Table 19. Frame Comparison of Impact Simulations for Concrete Median Barrier – Top View

Time(s)	0	0.78
1st Impact		
2nd Impact		
3rd Impact		
4th Impact		
Time	1.16	1.68
1st Impact		
2nd Impact		
3rd Impact		
4th Impact		
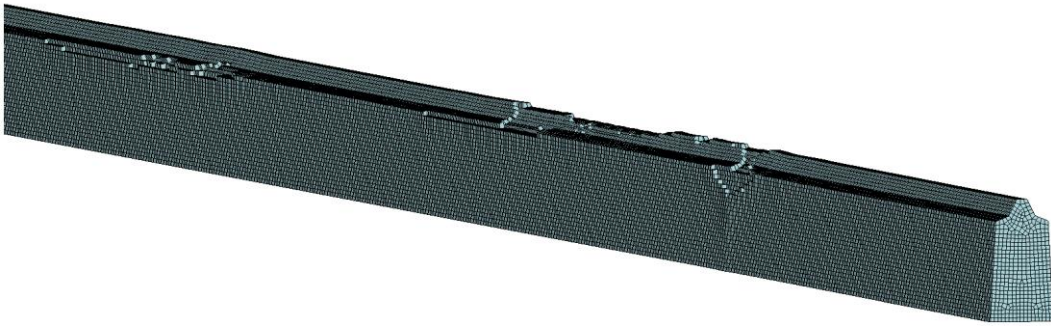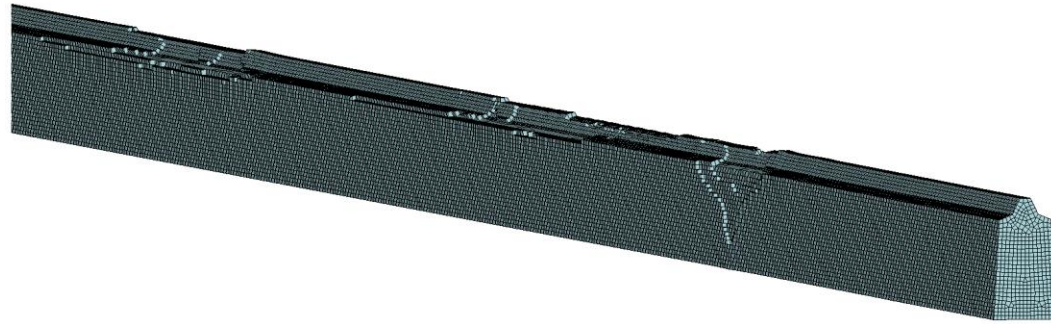
4.2.4 Barrier Strength

Concrete erosion and steel damage at the top of the Concrete Median barrier due to four consecutive tractor-van trailer impacts can be observed in Table 20. Erosion parameter for concrete was defined such that the elements are deleted when the effective plastic strain in the concrete exceeds 9.45%. Table 21 shows the concrete effective plastic strain in impact side and back side of the barrier respectively for the impacts. Cracks are likely to occur at the area shown in red where the strain values are the highest. Table 22 shows and discusses the plastic strains in the steel reinforcement of the barrier at the end of each impact. The steel reinforcement modeled as beam elements is not considered in the calculations if the maximum plastic strain exceeds 20%. Reinforcement in navy blue represents negligible or no plastic strain.

Table 20. Erosion of Concrete Median Barrier - Four Consecutive Impact Simulations
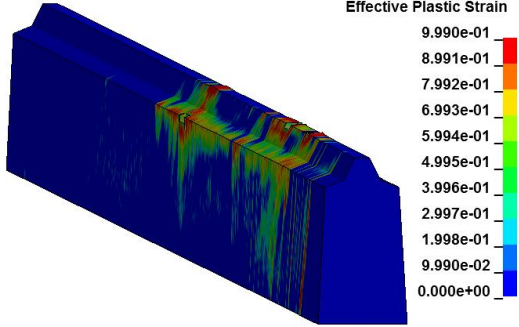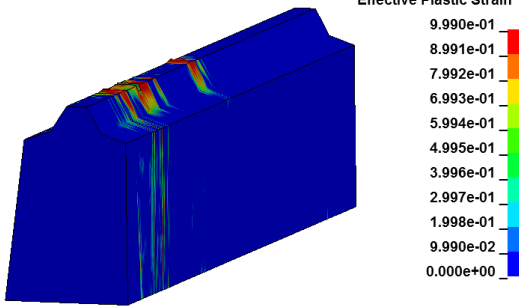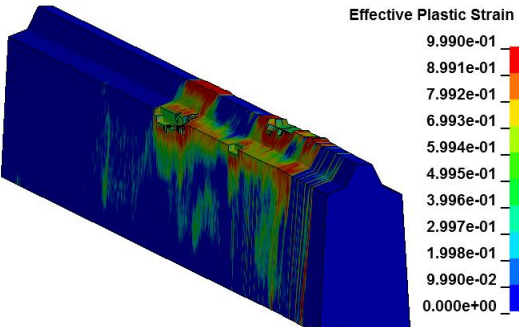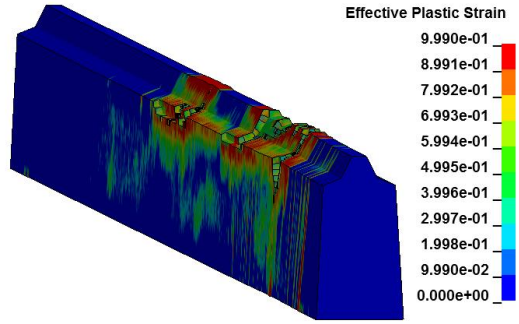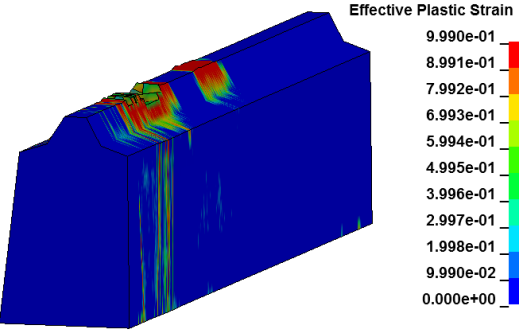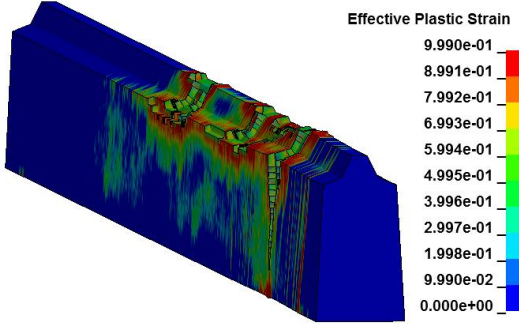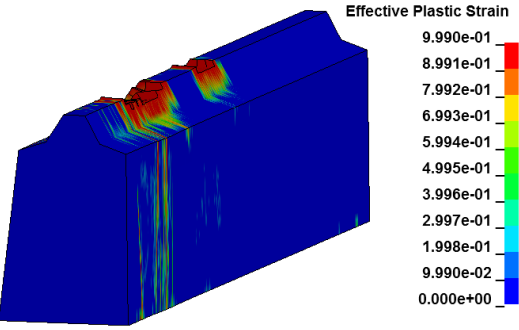
1st Impact	
	Erosion of a single line of elements occurred at top-front of the barrier protrusion beginning at about 9194 mm (30.2 ft.) from the upstream end of the barrier and extended downstream for about 189 mm (0.62 ft.). Another segment of erosion occurred at the top of the barrier protrusion beginning at about 12500 mm (41 ft.) and extended downstream for about 870 mm (2.85 ft.) Almost all of the top layer of 38 mm solid elements from front side (impact side) to back side of the barrier protrusion was eroded at this described location. Additional damage occurred at the front-edge of the barrier (below protrusion) beginning at 27121 mm (89 ft.) from upstream end and stretched 1062 mm (3.5 ft.) downstream.
2nd Impact	
	Looking from the upstream end, the first eroded segment grew and now began about 8929 mm (29.3 ft.) from the end and extended about 457 mm (1.5 ft.); complete top layer of elements on the barrier protrusion were eroded. The second eroded segment also grew and now began about 12350 mm (40.5 ft.) from the upstream end, it stretched about 4442 mm (14.6 ft.). All of the top layer of elements was eroded with some second-to-top and third-to-top layer elements also eroding intermittently. Erosion occurred at a new location at the front-edge of the barrier beginning at about 16831 mm (55.2 ft.); a single line of elements eroded for a length of about 1745 mm (5.73 ft.). Existing front edge damage grew which now began at 26854 mm (88 ft.) from upstream end and stretched 5885 mm (19.3 ft.) downstream.

Table 20 Continued
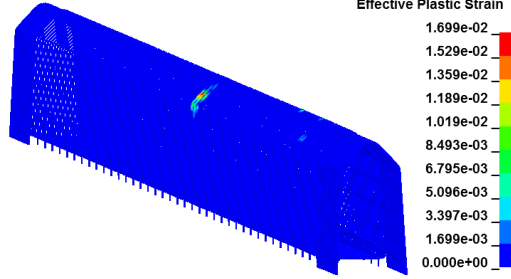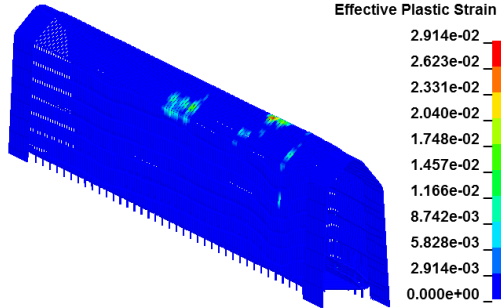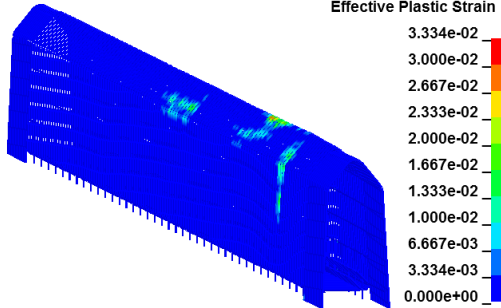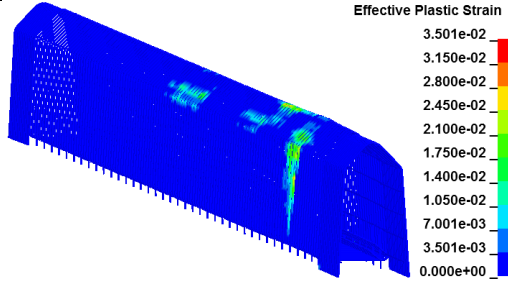
3rd Impact	
	The first eroded segment on the top protrusion grew further and now began about 8548 mm (28.0 ft.) from the upstream end and extended about 2624 mm (8.6 ft.). The erosion also grew downward on front face of the barrier reaching the front edge of the barrier (below the protrusion) and further down; up to eight layers of elements were eroded below the front edge in a V-shape. The second eroded segment also grew and now began about 12194 mm (40.0 ft.) from the upstream end, it stretched about 8012 mm (26.3 ft.). All of the top layer of elements was eroded up to more than half of the stretch, the erosion then progressed downward to the front edge (below the protrusion) and transitioned to a single layer of front edge elements for the final third of its length. The front edge damage that began at 26854 mm (88 ft.) grew slightly in width and length and now stretched 6721 mm (22.1 ft.).
4th Impact	
	The first eroded segment on the top protrusion grew further and now began about 8396 mm (27.5 ft.) from the upstream end, it extended to merge into the second eroded segment. The V-shaped erosion on the front face extended further down and up to fifth layer of elements from 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 23018 mm (75.5 ft.) from the upstream end. The furthest front edge damage now stretched 7557 mm (24.8 ft.) beginning at 26550 mm (87.1 ft.) from upstream end, it mainly progressed upward towards the crown of the protrusion.

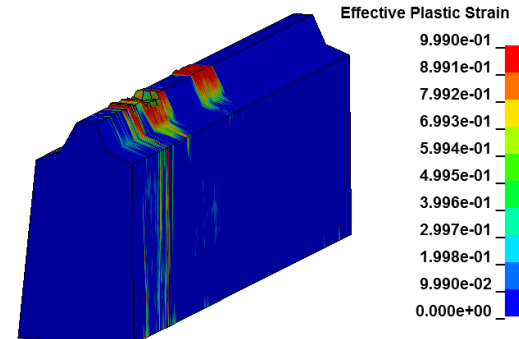**Table 21. Concrete Effective Plastic Strain of Concrete Median Barrier - Four Consecutive Impact Simulations**

Truck No.	Concrete Effective Plastic Strain – Impact Side	Concrete Effective Plastic Strain –Back Side
1st		
2nd		
3rd		
4th		

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Table 22. Steel Plastic Strain of Concrete Median Barrier - Four Consecutive Impact Simulations

.	Plastic Strain
1st Impact	Effective Plastic Strain 1.699e-02 1.529e-02 1.359e-02 1.189e-02 1.019e-02 8.493e-03 6.795e-03 5.096e-03 3.397e-03 1.699e-03 0.000e+00
	The maximum plastic strain of about 1.7% is in traverse rebar in a small region at the top of the barrier. Most of the reinforcement has negligible or no plastic strain.
2nd Impact	Effective Plastic Strain 2.914e-02 2.623e-02 2.331e-02 2.040e-02 1.748e-02 1.457e-02 1.166e-02 8.742e-03 5.828e-03 2.914e-03 0.000e+00
	The maximum plastic strain of about 2.9% is in traverse rebar in a small region at the top of the barrier. Most of the reinforcement has negligible or no plastic strain.
3rd Impact	Effective Plastic Strain 3.334e-02 3.000e-02 2.667e-02 2.333e-02 2.000e-02 1.667e-02 1.333e-02 1.000e-02 6.667e-03 3.334e-03 0.000e+00
	The maximum plastic strain of about 3.3% is in traverse rebar in a small region towards the top end of the barrier. Most of the reinforcement has negligible or no plastic strain.
4th Impact	Effective Plastic Strain 3.501e-02 3.150e-02 2.800e-02 2.450e-02 2.100e-02 1.750e-02 1.400e-02 1.050e-02 7.001e-03 3.501e-03 0.000e+00
	The maximum plastic strain of about 3.5% is in traverse rebar in a small region at the top of the barrier. Most of the reinforcement has negligible or no plastic strain.

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4.2.5 Occupant Risk

The summary of results of occupant risk assessment and angular displacement for the four consecutive tractor-van trailer impacts into Concrete Median barrier are shown in Table 23. Occupant risk assessment was performed based on applicable safety evaluation criteria defined in MASH using TRAP program [1, 17]. The tractor-van trailer models stayed upright and rollover did not occur during the simulated impact events. The impact velocities and ridedown accelerations observed in the impacts are below the MASH recommended limits [1].

Table 23. 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

4.3 Comparison of Vehicle roll

This section compares the vehicle roll values observed at the rear-axle during the truck platoon impacts into for Manitoba concrete bridge rail and Concrete Median barrier.

Figure 18 shows the ascending trend of vehicle roll observed at the rear axle during the five consecutive tractor-trailer impacts into Manitoba concrete bridge rail. Similarly, the ascending

trend of vehicle roll at the rear axle during four consecutive tractor-trailer impacts into Concrete Median barrier is shown in Figure 19. Figure 20 compares the roll angle for the first and fourth impact into each barrier type. While the vehicle roll increased from first to fourth impact for both barriers, it can be noted that the tractor-trailer impacts into the taller Manitoba concrete bridge rail were more stable in comparison to the shorter Concrete median barrier. The vehicle roll values for the taller barrier were reduced almost half of the values observed for the shorter barrier.
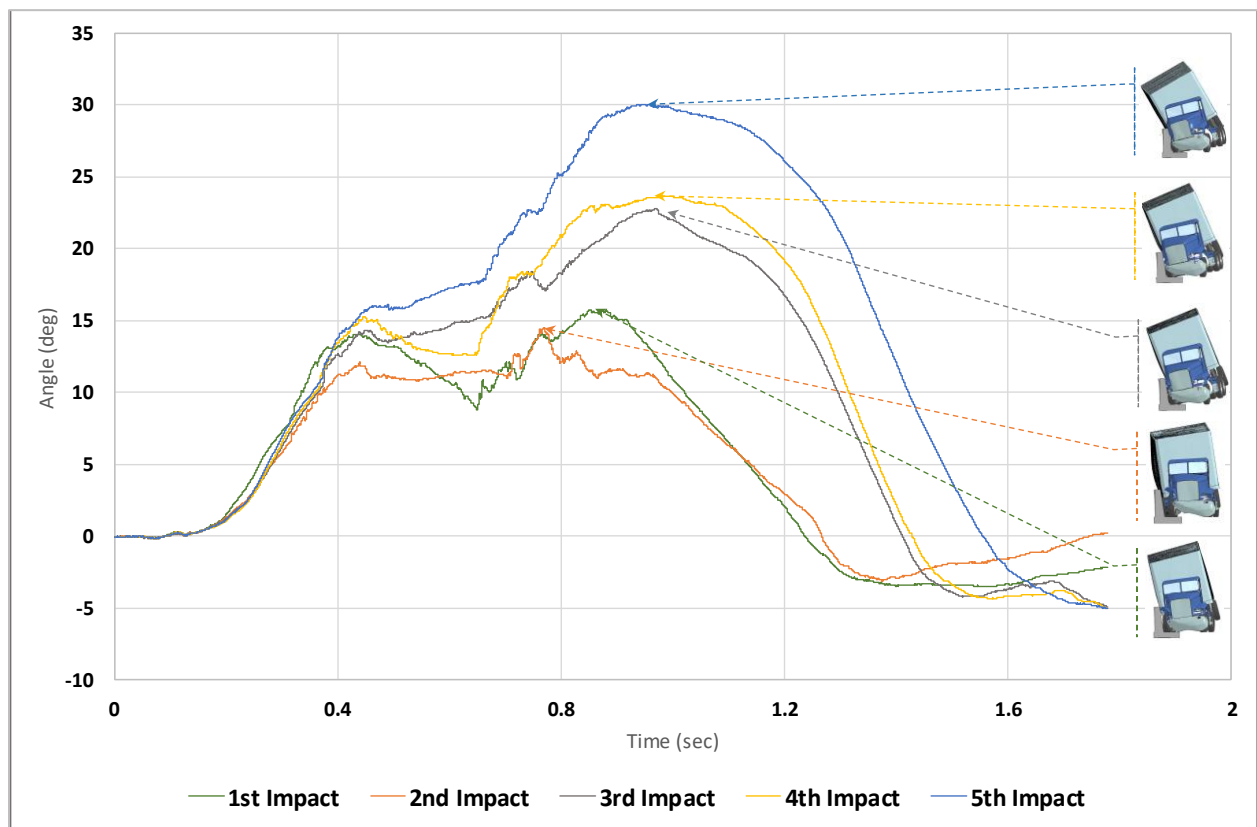
Figure 18. Comparison of trailer rear-axle roll for truck platoon impact into Manitoba Concrete Bridge Rail
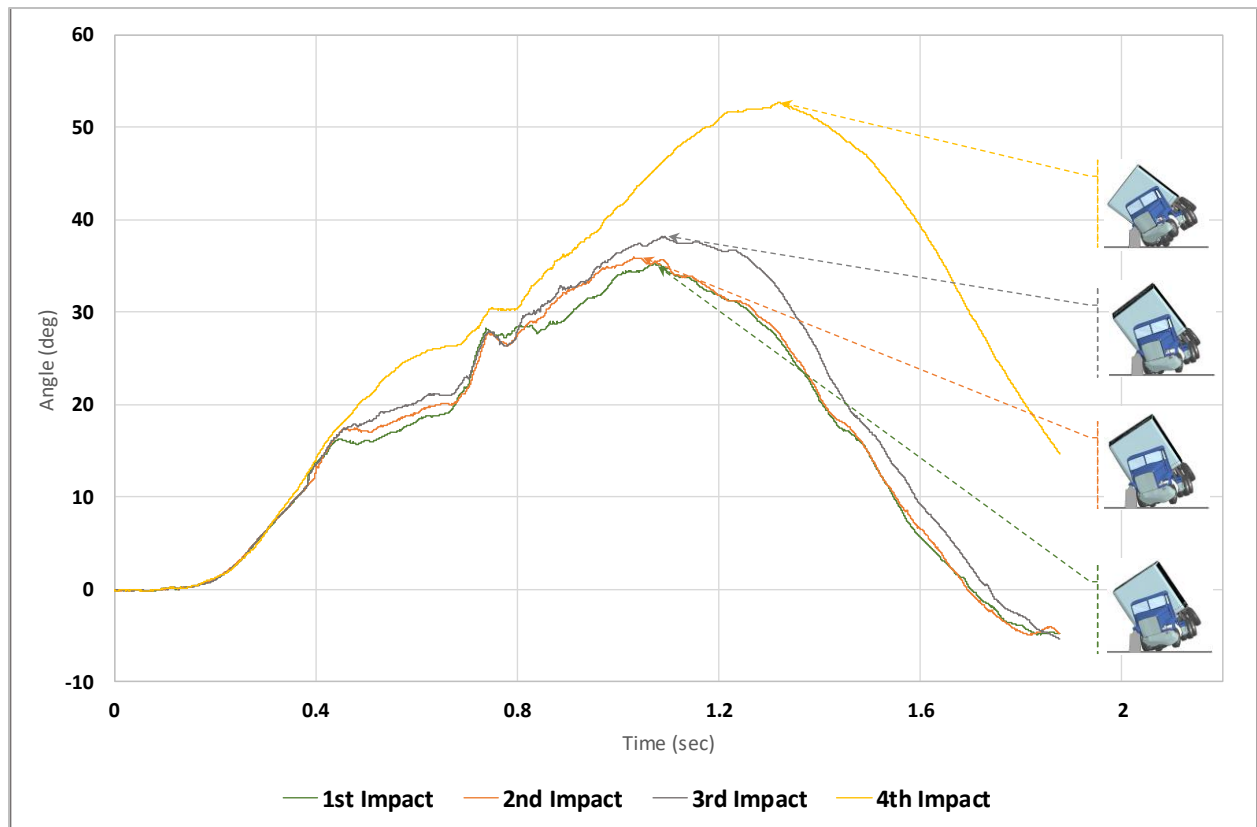
Figure 19. Comparison of trailer rear-axle roll for truck platoon impact into Concrete Median Barrier
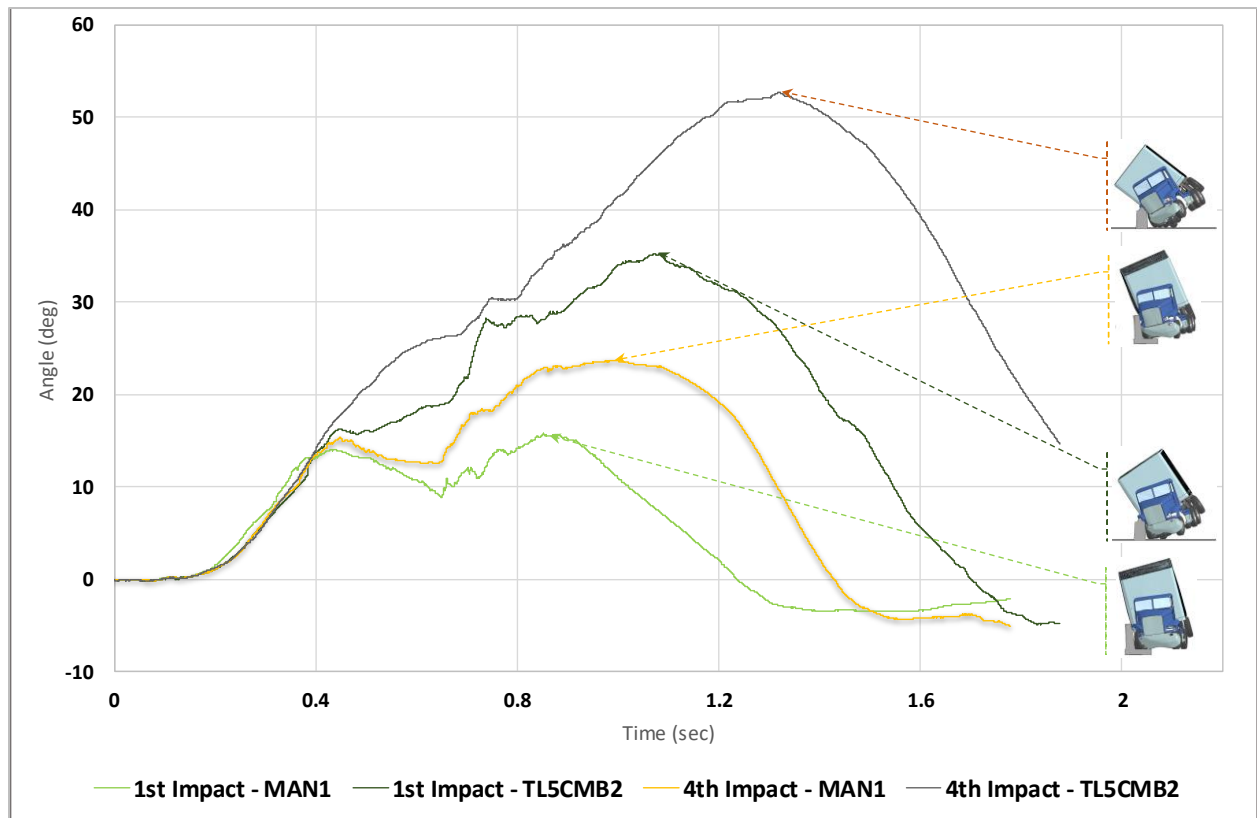
Figure 20. Comparison of trailer rear-axle roll for truck platoon impact into Manitoba Concrete Bridge Rail and Concrete Median Barrier

5. CONCLUSIONS AND RECOMMENDATIONS

Detailed FEA models of the Manitoba concrete bridge rail and the Concrete Median barrier were consecutively impacted, under MASH TL5 conditions, by five and four tractor-van trailer models respectively. These simulations were analyzed to assess the structural adequacy, vehicle stability and occupant risk in the event of errant truck platoons. Due to the impacts at given conditions, final permanent deflection 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 Manitoba concrete bridge rail deck, representing deck concrete failure, did not occur even though strain values close to maximum effective plastic strain of 9.45% were observed in longitudinal direction near the point of impact. Cracks are likely to occur in this highly strained region of the deck, during the 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 during any of the in-series impact into the barriers selected for this study. In addition, the occupant risk metrics were within the acceptable limits defined by MASH and major injuries are not expected to occur during any of the impact events.

The analysis results suggest that the Manitoba concrete bridge rail and the Concrete Median barrier are potentially capable of containing and redirecting multiple impacts at MASH TL5 impact conditions, while posing minimal risk to the occupants. 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 during impact against errant truck platoons. As the top of the impacted barrier may erode after initial impacts, extra height in addition to minimum height defined by

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MASH TL5 will be critical to maintain stability of the following vehicles that will impact the barrier. So, in the regions where truck platooning is likely to be deployed and new barriers are required, it is recommended to use TL5 barriers taller than minimum height of 1067 mm (42 in).

It is highly recommended to perform additional studies to identify the possible impact conditions for the following truck impacts, resulting from errant truck platoons. Even though, the first impact for each system was evaluated against the respective full-scale crash test, there was no data to validate the following impact simulations. It is recommended to conduct multiple impact tests in order to validate the simulation results of following impacts. It will allow researchers to make concrete conclusions before fully considering the barrier systems sufficient for multiple impacts at MASH TL5 conditions. In addition, considering department 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.

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