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Development of a Next-Generation Non-Proprietary Portable Concrete Barrier

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DEVELOPMENT OF A NEXT-GENERATION NON-PROPRIETARY PORTABLE CONCRETE BARRIER

by

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Portable concrete barriers (PCBs) are segmented barriers made of precast concrete units that are connected by various load-bearing hardware. PCBs are typically used to shield work zones by redirecting errant vehicles upon impact with the barrier system. Most commonly-available PCBs have demonstrated performance issues arising from the sloped face of the barrier, which encourages vehicles to pitch and roll during impact, potentially resulting in vehicle rollover. Concerns also exist regarding the large dynamic deflections exhibited by these systems that can encroach upon the protected work zone or require anchoring to prevent large displacements. In addition to these concerns, the American Association of State Highway and Transportation Officials (AASHTO) updated the *Manual for Assessing Safety Hardware* (MASH) in 2016, which improved the criteria for evaluating roadside safety devices and required the re-evaluation of barrier systems developed before the updated standards were published. Thus, an opportunity existed to develop a next-generation PCB system capable of meeting the new MASH 2016 criteria while addressing the concerns of the current generation of PCBs.

The objective of this research effort funded by the Mid-America Transportation Center (MATC) was to further develop and investigate PCB concept designs that were brainstormed under a parallel research effort at the Midwest Roadside Safety Facility (MwRSF) funded by the Wisconsin Department of Transportation. This research

consisted of the development of finite element models of the PCB design concepts for use in LS-DYNA simulations, followed by the comparison of the simulation results to a current PCB system that has been previously modeled and validated.

The simulation analysis identified three PCB concepts as viable designs, while three other PCB concepts were not recommended based on the simulation performance. Upon completion of the simulation analysis, the simulation results of the six PCB concepts were presented to Midwest Pooled Fund Program member states. Finally, a single concept, that used interlocking and staggered precast concrete segments without the need for connection hardware, was selected for further design and full-scale crash testing in the next phase of the research.

ACKNOWLEDGEMENTS

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Chapter 1 Introduction

1.1 Background

Portable concrete barriers (PCBs) are segmented units which are attached end-to-end by a load-bearing connection. PCBs are typically used to prevent errant vehicles from leaving the roadway and to safely redirect vehicles that have impacted the barrier, often where limited deflection is desired during vehicle impacts, such as on bridge decks and within work-zones. In other cases, PCBs are used in long-term installations acting as a median barrier and/or as a bridge rail. Most non-proprietary, portable barrier systems on the nation's highways consist of safety-shape or single-slope barrier segments fabricated from reinforced concrete materials. Most current PCB designs face problems:

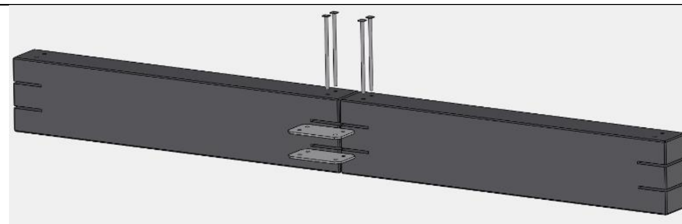
1. The sloped face of the barrier often allows impacting vehicles to pitch and roll as they impact the barrier, often causing unstable vehicle behavior that can result in vehicle rollover.
2. The segmented joints allow for significant rotation before transferring moment across the joint, resulting in large lateral barrier displacements, ranging from 19 to 80 in. Where deflections must be limited, anchoring or pinning the barrier segments to the pavement is required, which impedes installation and removal, exposes workers to traffic hazards, and causes pavement or bridge deck damage.

Furthermore, the Federal Highway Administration (FHWA) and the American Association of Highway and Transportation Officials (AASHTO) recently updated the *Manual for Assessing Safety Hardware* (MASH) in 2016, which is the standard for the evaluation of roadside safety hardware [1]. MASH 2016 includes implementation guidelines that require devices installed on federal-aid roadways after sunset dates to be evaluated under MASH 2016 criteria. December 31, 2019, was the sunset date for temporary work-zone devices, including portable barriers, and any devices used on projects after this date must have successfully passed MASH 2016 testing. However, devices used on projects before this date and successfully tested under National Cooperative Highway Research Program (NCHRP) Report 350 or the 2009 edition of MASH, may continue to be used throughout their normal service lives [2, 3].

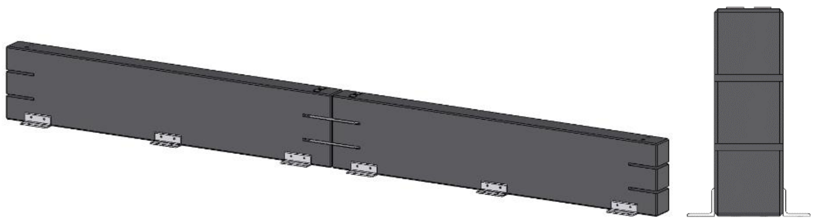
Thus, a critical need exists to develop a high-performance portable barrier system that meets MASH safety criteria, while addressing the deflection, stability, and durability concerns of current portable barrier designs. In 2016, this research need was raised by roadside safety researchers at the Transportation Research Board (TRB) mid-year meeting, sponsored by Committee AFB20, Roadside Safety Design [4].

An existing research effort at Midwest Roadside Safety Facility (MwRSF) had been underway with the Wisconsin Department of Transportation (WisDOT) to develop a non-proprietary, high-performance PCB capable of meeting the MASH Test Level 3 (TL-3) safety requirements with reduced deflections and increased vehicle stability as compared to existing, widely used PCB systems. At the time this Mid-America Transportation Center (MATC) project began, the WisDOT effort had completed a thorough review of existing portable barrier technology, developed design criteria, partially investigated alternative materials to reinforced concrete, and drafted several initial design concepts, as shown in Figure 1. Further design and crashworthiness analysis of concept designs required advanced computer simulations.

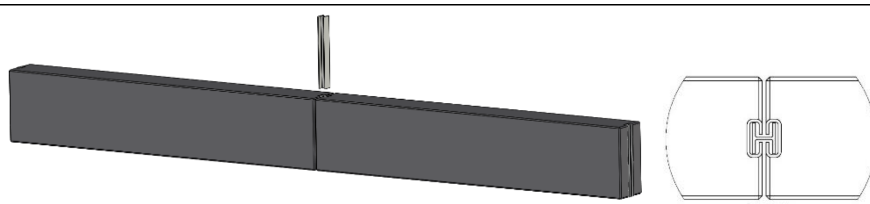
This MATC research project aimed to further investigate potential PCB design concepts through computational simulations using LS-DYNA [5], as a cost-effective method of investigating potential modifications and discovering performance issues prior to full-scale crash testing of the final design concept. The optimized design through computer simulations will be recommended for full-scale crash testing to MASH 2016 in subsequent research supported by the Midwest Pooled Fund Program.



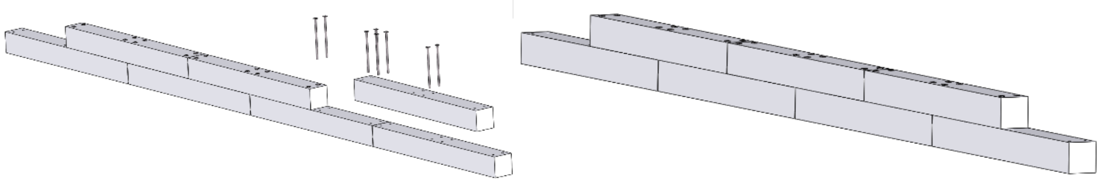
Vertical PCB with Pin and Plate Connection



Vertical PCB with Pin and Plate Connection with Feet



Vertical PCB with I-Beam Connection



Staggered Vertical PCB Concept

Figure 1. Initial PCB Design Concepts – Brainstormed from WisDOT Project

1.2 Objectives

The objective of this MATC-funded research effort was to (1) analyze the candidate PCB design concepts, including various shapes/profiles and joint systems, and

(2) to use computer simulations to evaluate crash performance and feasibility of concepts. The optimized configuration(s) will be recommended for full-scale crash testing and further development and implementation. This finite element simulation effort using an advanced nonlinear LS-DYNA package critically assists the development and implementation of high-performance PCBs as it represents a cost-effective and reliable means of analyzing multiple design concepts and impact scenarios as compared to limited full-scale crash testing.

A portable barrier system with a vertical or near-vertical front face would reduce and/or eliminate the potential for vehicle instability, while a system with modified connections could reduce dynamic barrier deflections. The new barrier system should have a practical length and weight such that typical construction equipment can be used for placement and, repositioning. The system should offer improved durability through modifications to the barrier geometry, end-to-end connection, and structure.

1.3 Research Approach

As previously mentioned, a thorough literature review of existing PCB technology has been executed as part of an ongoing project, and materials alternative to reinforced concrete and initial design concepts were partially investigated. To continue this comprehensive research effort, a series of activities were executed: (1) design concepts were analyzed based on feedback from state departments of transportation (DOTs), and (2) LS-DYNA computer simulations were conducted on candidate designs. Throughout the project, feedback was incrementally sought from state DOT representatives to guide and support the research developments. The design focused on a free-standing barrier, but recommendations are made for future studies on anchoring the portable barrier and extending the PCB applications to median or permanent barriers.

In this report, the first chapter provides background information, project objectives, and the research approach. Chapter 2 summarizes the literature review, which consisted of a review of existing PCB systems and alternative concrete materials, as well as an explanation of a survey sent to the Midwest Pooled Fund Program member states to gather input for establishing PCB design criteria. Chapter 3 lists the design criteria for the new PCB system, each of the brainstormed concept designs, and specifies which PCB concepts were selected for further development and investigation. Chapter 4 details the process of creating the LS-DYNA models for each concept design, as well as explains several modifications made to the PCB concepts throughout the modeling process. Chapter 4 also details the simulation results for all PCB concepts and their variations. Chapter 5 shows direct comparisons for the simulation results in the form of bar plots and documents the results of a second survey sent to the Midwest Pooled Fund Program member states which clarified responses from the previous survey and ranked PCB concepts by preference. Chapter 6 summarizes this research effort, details the conclusions, and discusses plans for future work.

Chapter 2 Literature Review

A comprehensive literature review of existing PCB designs was conducted under the related WisDOT project [6]. The literature review consisted of a summary of NCHRP Report No. 22-36, titled *Synthesis of the Performance of Portable Concrete Barriers*, which investigated PCB shapes, connections, anchorage, transportation, installation, and durability [7]. MwRSF reviewed additional publications, including FHWA eligibility letters, to investigate simulation and full-scale crash test results. Literature was also gathered to explore alternative concrete materials for potential use in the PCB systems. In addition to the review of existing literature, a survey was sent to the member states of the Midwest Pooled Fund Program and several PCB fabricators and installers to identify the design criteria for the next generation PCB system.

2.1 Existing Portable Concrete Barrier Systems

Many different designs for PCB systems are currently in use; however, these designs vary in terms of shape, connection type, length, anchorage, and other characteristics. Most PCB systems currently in use have evolved from the original GM shape barrier into either vertical, single slope, or safety shape, which includes the New Jersey shape and F-shape. The GM shape was developed by General Motors and has a shallow lower slope and a steep upper slope, as shown in Figure 2. This shape allowed vehicles impacting at slow speeds and low angles to climb the lower face and be redirected, while limiting the amount of contact with the vehicle body, thus reducing vehicle damage. Vehicles impacting at higher speeds and higher angles are redirected by the steep upper slope of the barrier [8].

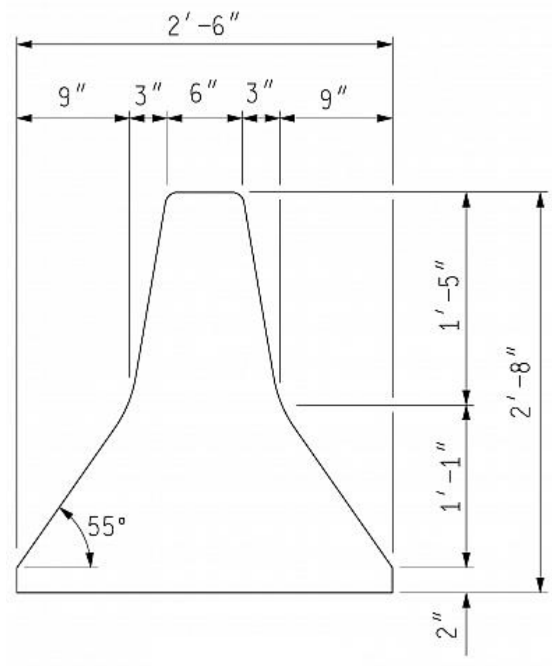
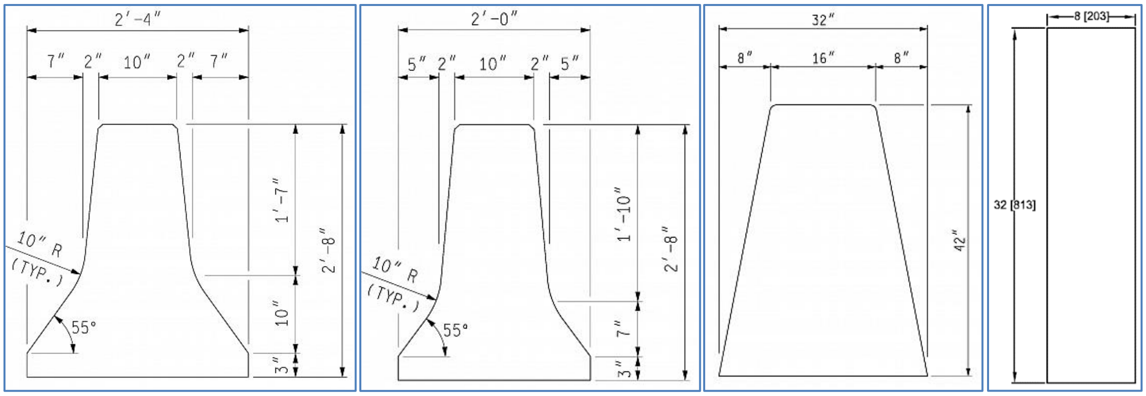


Figure 2. GM Shape PCB [9]

Through crash testing, the GM shape was refined into the New Jersey shape by the New Jersey Department of Transportation and featured a shorter lower slope. The New Jersey shape was further refined into the F-Shape in order to reduce vehicle pitch and roll during impact.

Vertical barriers do not have sloped faces, and thus result in only horizontal forces exerted on impacting vehicles. This outcome has the benefit of reducing vehicle pitch and roll, but increases peak lateral impact forces and creates potential for head slap against tall barriers since the vehicle does not roll away from the barrier. Single-slope barriers were developed to balance these benefits and disadvantages, which generally have a front slope ranging between 9 and 11 degrees. Typical cross-sections of New Jersey, F-shape, single slope, and vertical PCB shapes are shown in Figure 3.



(a) New Jersey (b) F-Shape (c) Single Slope (d) Vertical

Figure 3. Typical PCB Shapes. (a) New Jersey, (b) F-Shape, (c) Single Slope, and (d) Vertical [6]

Barrier connection types were also collected as part of the WisDOT literature review and included pin and loop, cross-bolt, interlocking, and drop-key designs. Pin and loop connections feature a pin that is dropped into loops extending from the ends of adjacent barrier segments. Cross-bolt designs consist of two threaded rods connecting adjacent segments, which result in lower deflections than systems with other connections due to the ability to tighten the connection. Interlocking connections were considered a connection between two adjacent segments that does not require external hardware. Drop-key or key and keyway connections feature a key that is dropped or inserted into a keyway cast into the ends of each segment. Pin and loop designs were the most popular, representing about 60 percent of the barriers identified in the WisDOT study. Pin and loop designs were followed in popularity by interlocking connections with about 20 percent, drop-key connections with about 14 percent, and cross-bolt connections with about 6 percent of the identified barriers.

Other information gathered as part of the WisDOT literature review effort included barrier segment length, which ranged from 10 ft to 30 ft, barrier cost, and the details of any full-scale crash testing or simulation results that were available. Barrier segment length heavily influences system deflection, since deflection tends to increase with lower barrier mass and more connections, which are characteristic of shorter barrier segment lengths. Barrier cost was investigated in a past Texas Transportation Institute (TTI) study, which determined that the least costly barrier design in terms of fabrication, installation, and maintenance costs consists of a PCB with 30-ft long segments and pin and loop connections [10].

2.2 Alternative Concretes

Typically, PCB systems are made using ordinary Portland cement concrete. Alternative concretes offer improved performance compared to normal concrete but come at an increased cost. Alternatives include ultra-high performance concrete (UHPC), fiber reinforced concrete (FRC), and polymer concrete (PC). The WisDOT literature review detailed the advantages and disadvantages of each alternative concrete, as well as the data available for each type [6]. Discussion regarding the alternative concepts concluded that UHPC would not be recommended due to its high cost and complicated manufacturing processes. Further study, including a cost-benefit analysis, was recommended regarding the advantages that FRC and PC may provide when implemented into a PCB design. Given the high cost associated with alternative concretes and lack of research in PCBs, it was recommended that the new PCB system be designed using normal concrete, while alternative concretes could be further investigated after the implementation of the new design.

2.3 Design Criteria Survey

As part of the WisDOT-funded research effort, a survey was distributed to Midwest Pooled Fund Program member states and other state DOTs to establish PCB design criteria. The survey was also passed on to PCB fabricators, installers, and consultants. In total, 31 respondents completed the survey, while 28 incomplete survey responses were received. The incomplete responses were not included in the results. The survey consisted of sections regarding cost, material, durability, installation, safety performance, and anchorage. The complete survey and a breakdown of the results were provided in the WisDOT report [6].

The primary takeaways of the design criteria survey were that cost, durability, and ease of use were the most important concerns of the respondents. Respondents desired a barrier that would be similar in cost to current barrier designs, but most were willing to accommodate higher costs if it came with the advantage of a more durable barrier with longer service life. Most respondents also preferred barriers that measured 10 to 14 ft in length and weighed a maximum of 7,000 lb. A 32-in. tall barrier was requested by most respondents to simplify the transition to current barriers. Concrete barriers were preferred, but steel or plastic designs would be acceptable. The exploration of alternative concretes was also supported by most respondents. Respondents preferred free standing PCB deflections of less than 3 ft.

The survey included several questions that did not receive clear responses, including drainage needs, horizontal radius of curvature, and vertical curvature. The research team decided on reasonable temporary values for the design criteria determined by the unclear responses until further clarification could be gathered in a future survey.

The survey ended with free-response questions, which allowed respondents to voice concerns or provide other input that was not specifically requested. The free responses included concerns about cost of adaptation and requests for improved barrier connections, improved anchorage options, ease of inspection, and low dynamic deflection.

The primary design criteria identified from the survey are summarized below:

- Cost would be targeted to be $100 per linear foot or less with a focus on increased durability.
- Barrier material would focus on standard concrete with the potential to investigate alternative concrete materials in future phases of research. Steel would be considered for use as well.
- Barrier connections would be designed to be easy to inspect and require little to no tools to install.
- Maximum lateral barrier deflections would be limited to 36 in. or less.
- Barrier height would stay at 32 in., with segment lengths between 10 to 14 ft and a width of 24 in. or less.
- Barrier segment weight would be limited to 7,000 lb or less for accommodating lifting equipment restrictions.
- Designs would need to consider installation on curves with a radius ranging from 100 ft to 770 ft.
- Designs would also need to consider potential methods of anchorage and transition to other barrier systems, but these methods would not be fully developed during the current phase of research.

Chapter 3 Development of Design Concepts

3.1 Design Criteria

Design criteria for the development of a high-performance PCB concept were based on an evaluation of current designs found in the literature review as well as the feedback from the design criteria survey. These criteria served as guidance for developing and evaluating PCB design concepts rather than strict requirements, and thus any of the developed concepts may or may not meet each of the design criteria. However, all the concepts were aimed at exceeding as many criteria as possible.

While the new system must meet MASH TL-3 test requirements, it must also show improved vehicle stability. Concerns about vehicle instability due to the shape of the existing safety shape concrete barriers led the team to focus on near-vertical shapes for improvement in this area. The new barrier must also show reduced deflection compared to the existing designs. Most survey respondents requested lateral deflections below 3ft. Therefore, design concepts were aimed at having deflections no greater than 3ft or even lower, if possible.

The other design criteria detailed in the WisDOT project report included cost, material preference, barrier durability, factors affecting installation, and several other considerations. Criteria for the cost required that a new PCB system would need to be either less expensive than current designs or have a longer service life than current designs in order to rationalize the cost increase. Based on the survey information, the goal for barrier cost was set as less than or equal to $100 per linear foot. Criteria for material preference did not limit the system to any specific material; however, concrete was the most preferred material in the survey, so the PCB concepts used concrete as the main material. Steel was also considered for its increased durability compared to concrete but would require a much longer service life to make up for the increase in material cost. Other factors included the ability to transport the barrier segments, segment weight and length, and the ease of installation and inspection.

3.2 Portable Barrier Design Concepts

After the literature review was completed and the design criteria were defined, the research team developed PCB design concepts. For the initial concept development, complete structural design, as well as final details such as anchorage, lifting points, and drainage, were not included since they would be designed during a later phase of the project. However, the potential addition of these details was still considered, and the barrier and connection design needed to be considered structurally sound and reasonable to implement.

Around twenty PCB concepts were developed, but only sixteen were presented to WisDOT due to some designs being considered infeasible based on internal discussions. Concepts were numbered by the order in which they were brainstormed, and this numbering system was not adjusted after the elimination of the infeasible concepts. Of the sixteen concepts presented, fifteen concepts used concrete as the primary material, and one used steel as the primary material with a concrete ballast. Most of the design concepts used pins for connections, while some relied on their geometry to interlock with adjacent segments. The sixteen concepts presented to WisDOT are shown in Figures 4 through 19.

Concept no. 1, shown in Figure 4, featured vertical concrete barrier segments connected by two steel plates that slid horizontally into slots, with four pins dropped through holes and steel plates in the barrier. This design minimized the gap between barrier segments while keeping a more traditional connection design through the use of drop pins.

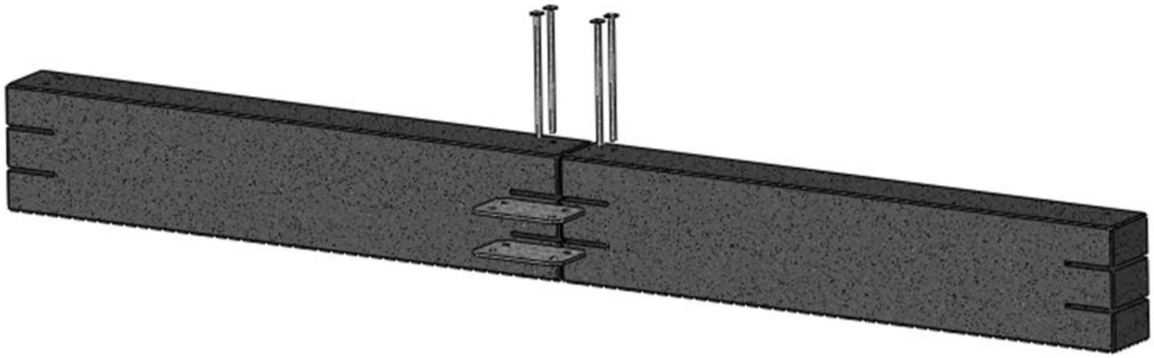


Figure 4. Concept No. 1

Concept no. 2, shown in Figure 5, featured a similar design to concept no. 1, but the barrier segments were made narrower to reduce weight. Steel feet were added at the bottom of the barrier to improve stability due to the reduced width while providing a potential location for anchoring the PCB system. This concept used the same connection hardware as concept no. 1.

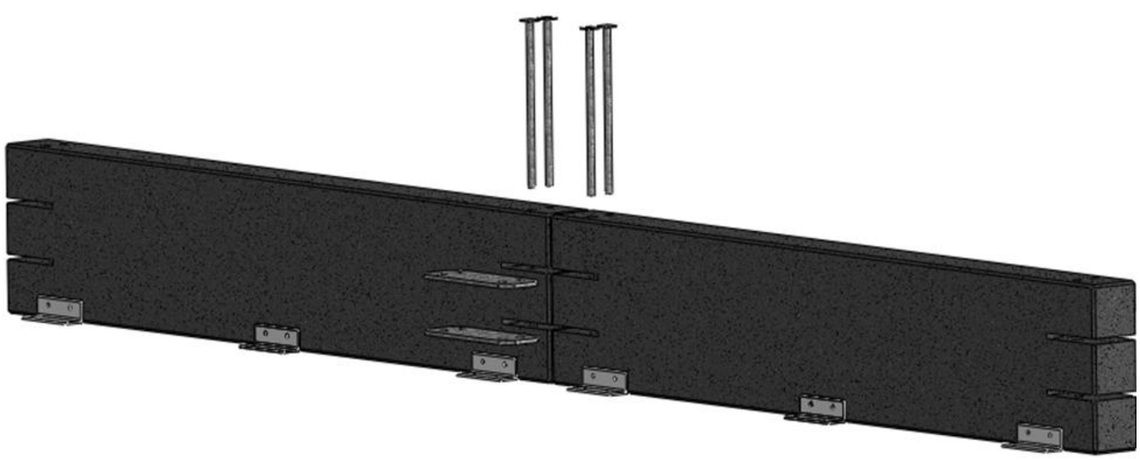


Figure 5. Concept No. 2

Concept no. 3, shown in Figure 6, was another variation of concept no. 1. It featured the same width as concept no. 1 but relocated the upper connection plate to the top face of the barrier. The connection hardware was otherwise identical to concept no. 1, which required two steel plates and four steel pins per connection.

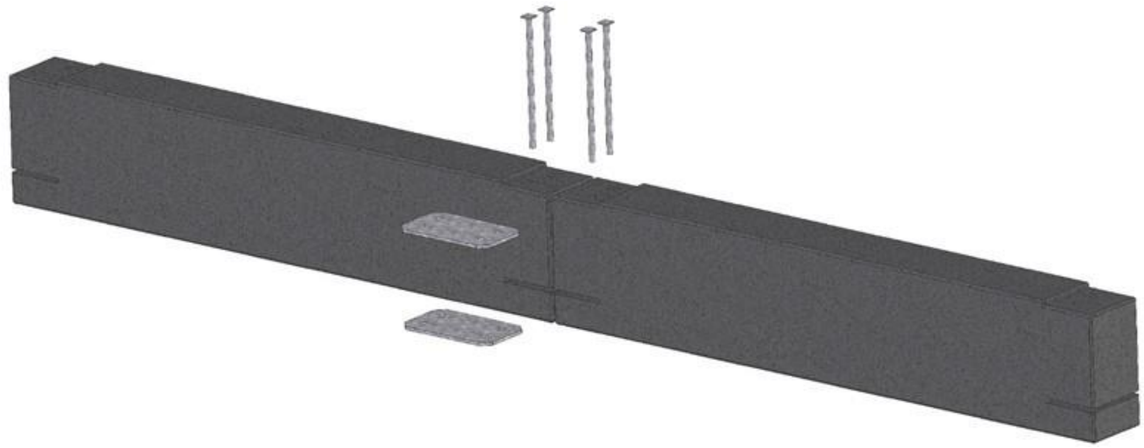


Figure 6. Concept No. 3

Concept no. 4, shown in Figure 7, featured concrete segments with vertical faces and used a key and keyway connection with an I-shaped key. This connection design reduced the number of pieces of connection hardware to only one piece per joint. However, this concept was not expected to provide as much moment continuity between segments as the previous concepts due to the single point of connection between adjacent barriers compared to the multiple pins used in concept nos. 1 through 3.

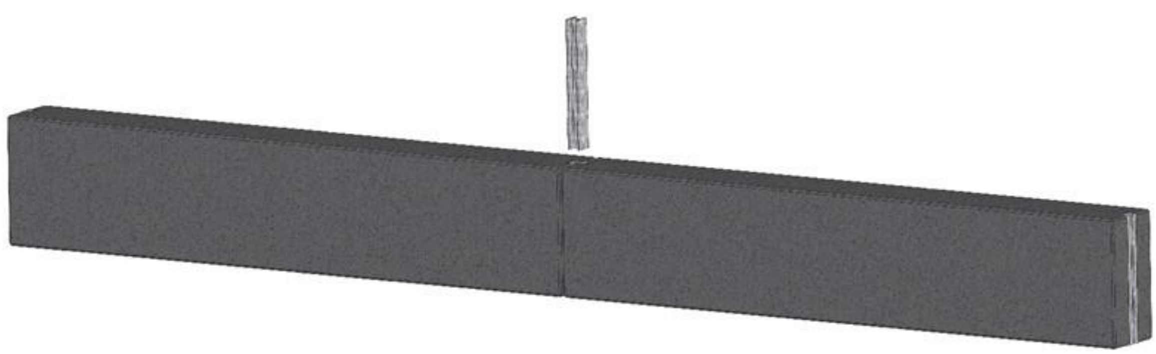


Figure 7. Concept No. 4

Concept no. 5, shown in Figure 8, featured a connection design consisting of two rectangular steel tube sections inserted into recesses in the ends of barrier segments which were connected by two drop-pins at each joint. However, due to the connection design, this concept only allowed barriers to be placed horizontally, and slid into place to accommodate the rectangular steel tube connection.

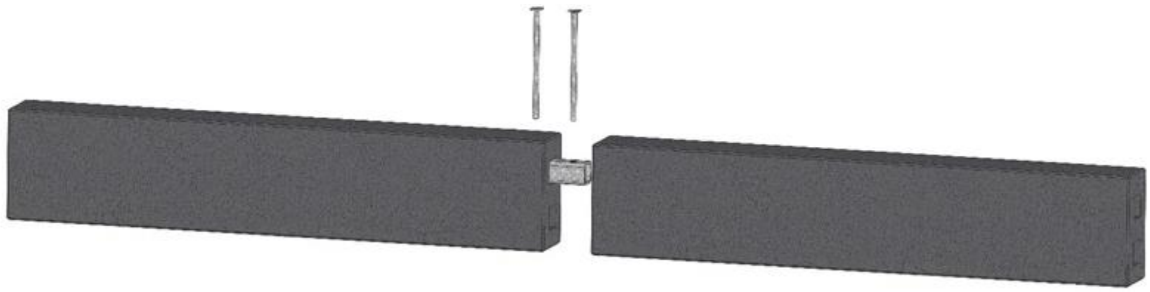


Figure 8. Concept No. 5

Concept No. 6, shown in Figure 9, featured an irregularly shaped barrier with ends that inserted into adjacent segments. The barrier segments were connected using two drop pins, a connection design that eliminated the use of additional connection hardware such as plates or tubes. Several concerns with this concept included the concentration of connection loads through a narrow section of concrete, the use of unsymmetric segments that needed to be slid into place and oriented correctly, and the potential need for special end sections to accommodate the irregular shape.

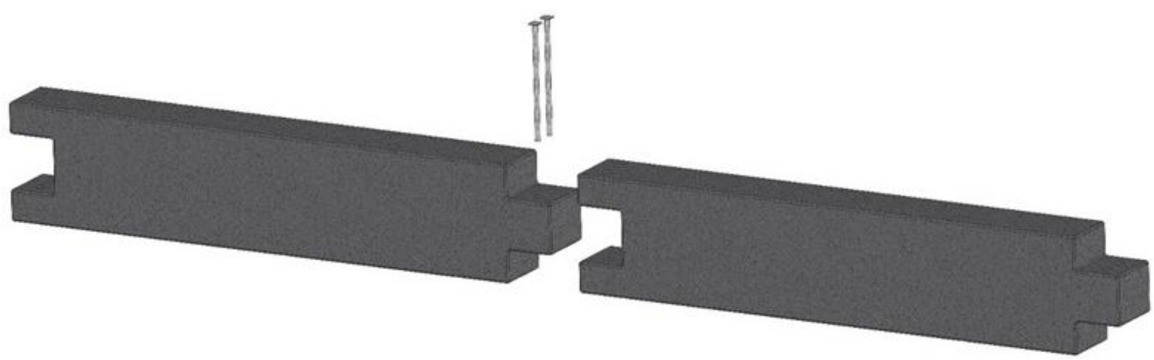


Figure 9. Concept No. 6

Concept no. 7, shown in Figure 10, featured two steel plates that were cast into each end of a barrier segment. The ends of the barrier segments were chamfered to expose holes in the corners of the steel plates, into which connected drop pins could be inserted. A pair of drop pins were connected by welding a steel plate at the top, and a pair of these connected drop pins were inserted on either side of the barrier connection. This design posed concerns due to the number of connection pieces required and the load transfer capacity of the connection.

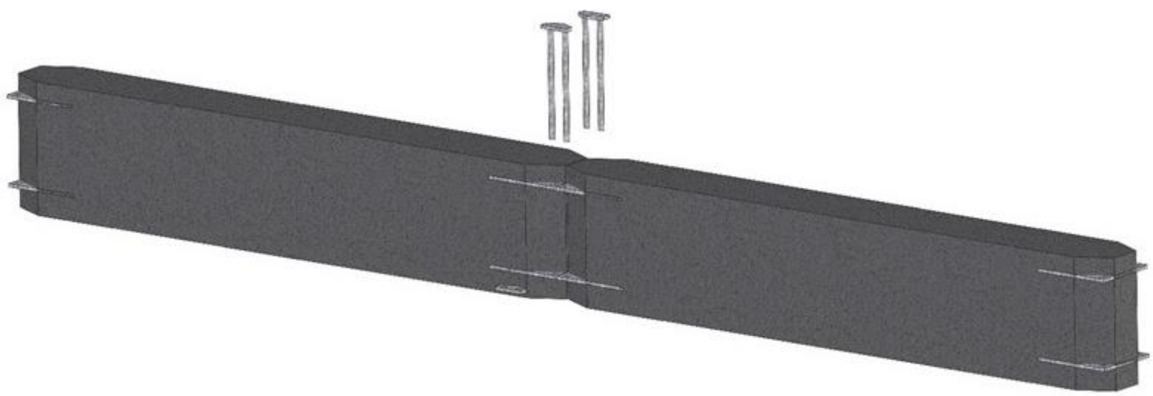


Figure 10. Concept No. 7

Concept no. 8, shown in Figure 11, featured a T-shaped concrete barrier section connected by two steel plates and four drop-pins per connection. One steel plate and two pins were used on each side of the joint between barrier segments. Concerns with this connection design stemmed from focusing the connection load through only the upper portion of the T-shaped cross section.

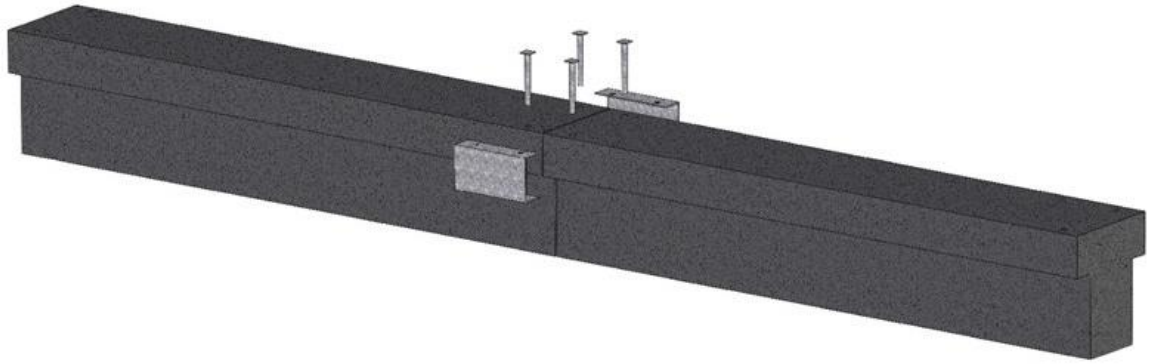


Figure 11. Concept No. 8

Concept no. 9, shown in Figure 12, features an irregularly shaped barrier with stepped ends that overlapped. The ends of the barrier segments were connected by two drop-pins per joint. However, concerns existed regarding focusing the connection load through a narrow barrier section and the potential need for special end sections to accommodate the stepped ends of the barrier segments.

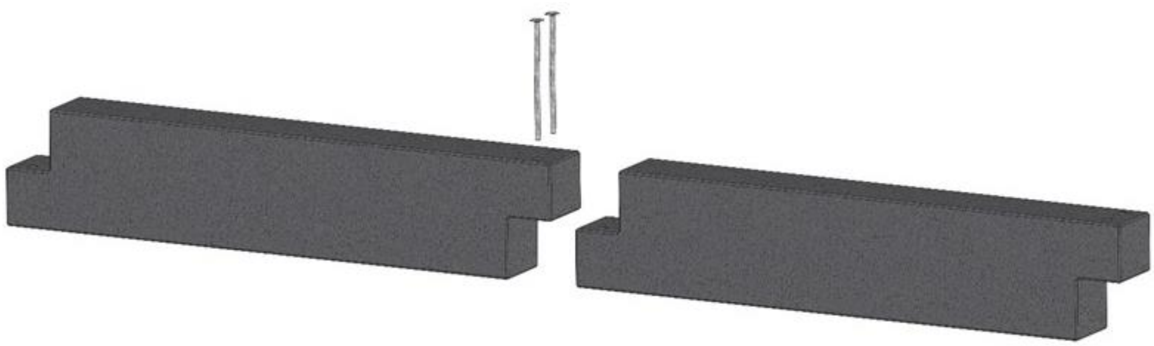


Figure 12. Concept No. 9

Concept no. 15 had two versions. The first version of concept no. 15, shown in Figure 13, was derived from concept no. 6 while the second version of concept no. 15, shown in Figure 14, was derived from concept no. 1. These two versions updated previous concepts to reduce the number of pieces of connection hardware. The connection design for each concept only used one connection pin per joint. Concept no. 15 version 1 eliminated one of the pins and reduced the barrier width. Concept no. 15

version 2 used two steel plates cast into one end of a barrier segment that were then inserted into slots in the opposite end of the adjacent barrier during installation, after which a pin was inserted to form the connection. However, reducing the number of pins was expected to reduce the moment continuity of the joints, which would in turn result in increased barrier deflections.

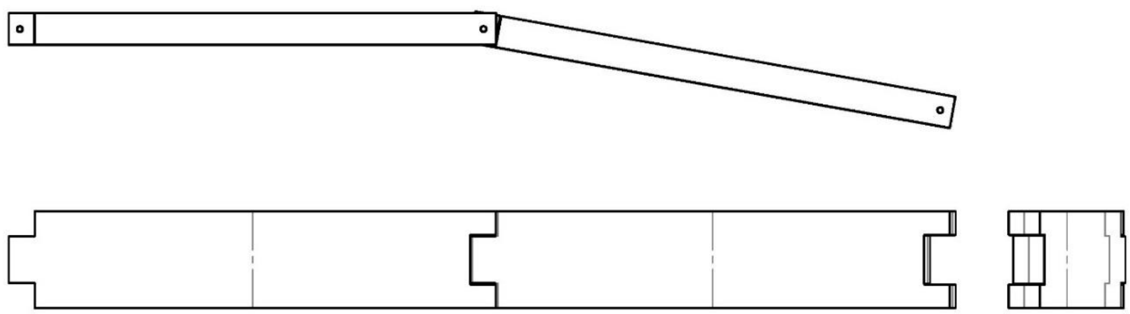


Figure 13. Concept No. 15 Version 1

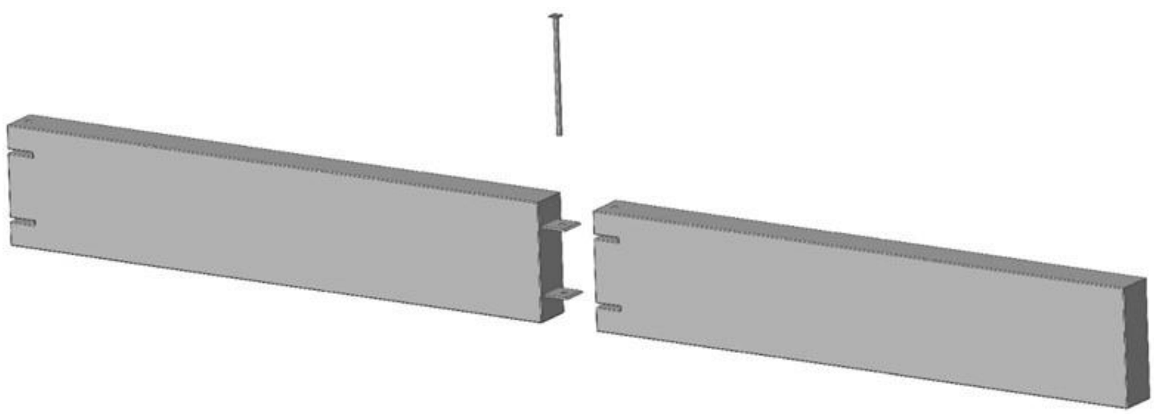


Figure 14. Concept No. 15 Version 2

Concept no. 16, shown in Figure 15, featured staggered and stacked barrier segments which were offset ½ of a barrier length longitudinally. The stacked segments were connected with two drop pins inserted on either end of every joint between segments, such that four pins were inserted through each top barrier segment, as shown. This connection design was simple and was expected to result in high moment continuity.

However, special end sections were likely to be needed for this concept due to the offset created by staggering the barrier segments.

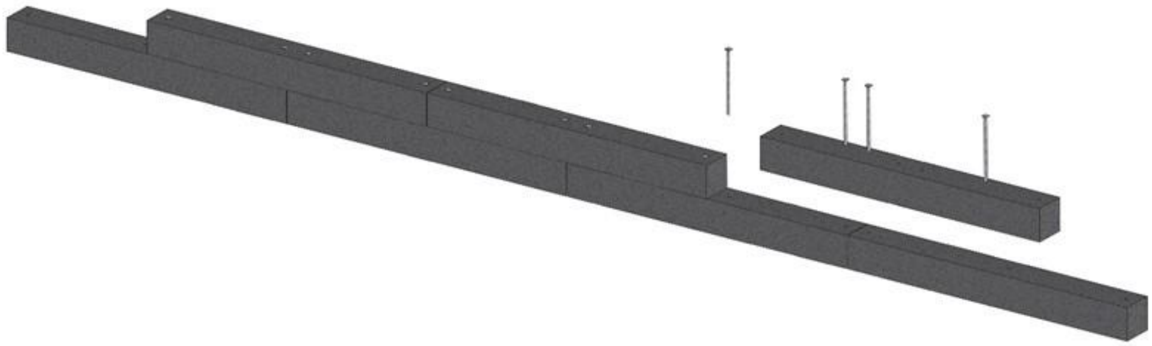


Figure 15. Concept No. 16

Concept no. 17, shown in Figure 16, featured solid concrete barrier segments connected by steel base plate assemblies at the bottom of each joint. During the installation process, the base plate assemblies would be placed on the roadway and the barrier segments would be set into place. This connection method eliminated the need for any other hardware or tools. However, the lack of shear transfer at the top of the barrier led to concerns regarding potential vehicle snag if the segments displaced relative to one another along the top of the barrier.

Figure 16. Concept No. 17

Concept no. 18, shown in Figure 17, was the only steel PCB due to the high cost of steel compared to concrete. This concept consisted of an upper and lower rectangular steel tube welded to steel plates on either side of the barrier. The space between the steel pieces was ballasted with concrete to increase barrier weight. The connection was formed by inserting two short sections of rectangular steel tube into the ends of the upper and lower tubes used to create the barrier segment, and a drop-pin was inserted from the top through the nested steel tubes on each side of the joint. Concept no. 18 was initially estimated to weigh roughly 3,500 lb and cost $250 per linear foot, which raised concerns regarding the effectiveness of the design due to its high cost and low weight.

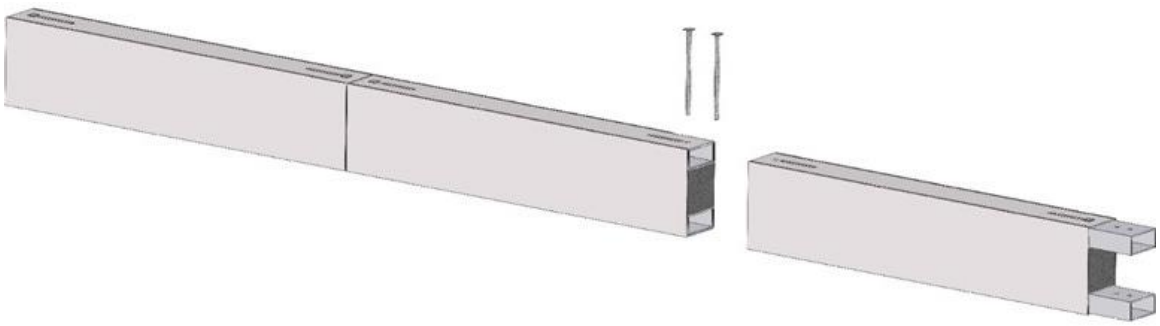


Figure 17. Concept No. 18

Concept no. 19, shown in Figure 18, featured staggered and interlocking concrete barrier segments. The bottom segments were an inverted T-shape, while the upper segments were an inverted U-shape. These shapes allowed the barrier segments to provide moment continuity throughout the length of the installation when longitudinally staggered by ½ of a segment length. This design also eliminated the need for external connection hardware. However, the barrier was expected to require special end sections to accommodate the staggering of the barrier segments.

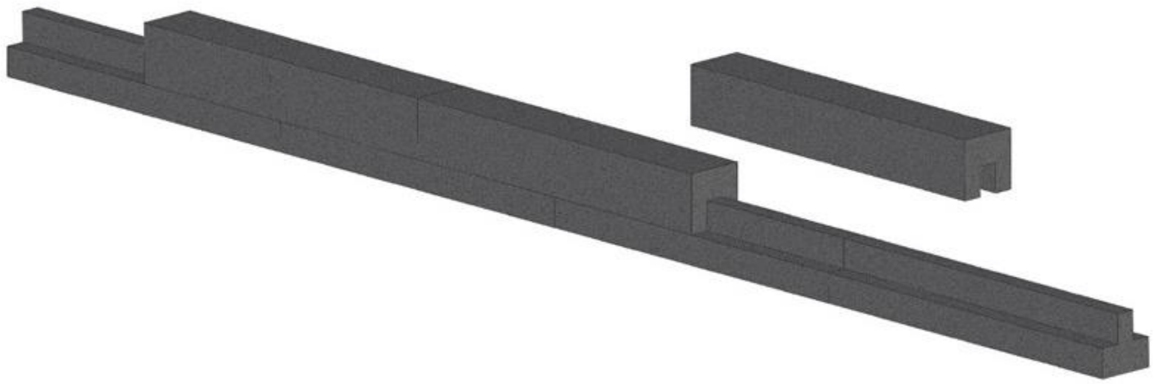


Figure 18. Concept No. 19

Concept no. 20, shown in Figure 19, featured a similar staggered and interlocking segment design as concept no. 19, however, the lower segment was not T-shaped, and the upper U-shaped segment extended the full height of the barrier. These shapes were expected to be easier to cast and reinforce, but there was concern regarding the lateral flexural strength of the thin lower concrete section and its lack of visibility when installed for inspection purposes.

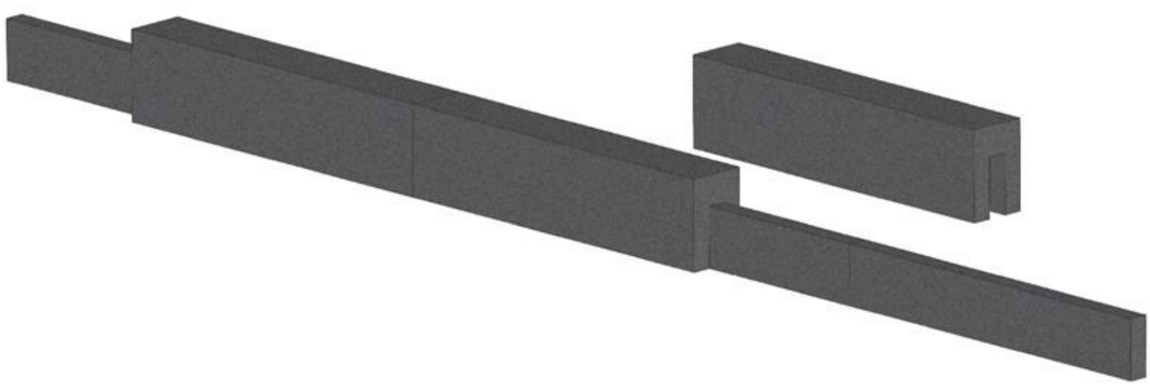


Figure 19. Concept No. 20

3.3 Selected Concepts for Simulation

Upon presentation and discussion with the adjacent project sponsor, WisDOT, five concepts were selected for further investigation through simulation as part of this MATC-funded research effort. The five concepts selected for further development and investigation were concept nos. 1, 2, 17, 18, and 19. Concept nos. 1, 2, 17, and 19 were concrete PCB systems, while concept no. 18 was a steel PCB system with a concrete ballast.

Concept no. 1 and concept no. 2 were selected due to their similarity to current PCB designs. Concept no. 17 was selected due to its simplicity, although there were concerns about vehicle snag that needed to be investigated. Concept no. 18 was selected because it was a steel concept that may prove to be more durable than other concrete PCB concepts, although concerns remained regarding barrier weight and cost. Concept no. 19 was selected due to its elimination of connection hardware, and thus, it was expected to be easier to install and inspect than other concepts. These selected concepts were expected to be the best performing, the most feasible to implement, and had the fewest points of concern as described above. The five selected concepts were then further investigated through computer simulation.

Chapter 4 LS-DYNA Simulation of Preferred Design Concepts

4.1 Baseline Model of Midwest F-Shape PCB

The five selected PCB concepts were evaluated using LS-DYNA finite element software to evaluate the safety performance and identify possible concerns with each design. The simulations for each of the concepts were compared to one another and a baseline model of the Midwest F-shape PCB. After reviewing preliminary simulation results, the research team decided to evaluate a sixth concept design that was expected to have favorable performance.

A model of the Midwest F-shape PCB was used as a baseline for concept comparison. This model was developed previously at MwRSF for determining the deflection of tie-down F-shape barriers and has been used in multiple other studies [11]. The PCB model consisted of sixteen F-shape PCB segments, connected using standard pin and loop connections, for a total length of approximately 200 ft. This PCB model provided the foundation and methodology from which the models of the PCB concepts were developed. An end barrier segment from this F-shape model is shown in Figure 20.

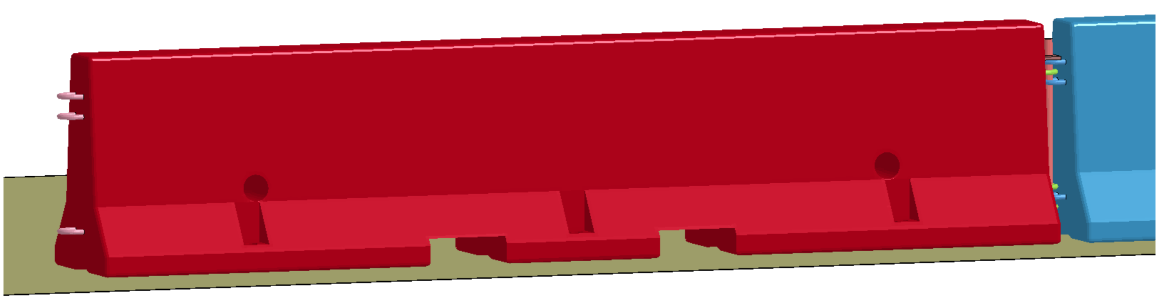


Figure 20. LS-DYNA Baseline Model of F-Shape PCB

The body of the PCB segments was represented using Belytschko-Tsay shell elements defined with a rigid material. The use of shell elements instead of solid elements offered improved contact between the barrier segments and the vehicle and made it easy to fillet the edges of the barrier. Since this essentially represented only the outer shape of the barrier with a hollow interior, each barrier segment had mass and rotational inertias defined at each segment's center of gravity. Mass and rotational inertia were determined from measurements taken in 3D-CAD software. The pin and loop connections between the barriers were modeled using fully-integrated solid elements. The loops were assigned a rigid material definition due to little to no deformation found in the previous testing, while the pins were assigned MAT_PIECEWISE_LINEAR PLASTICITY to appropriately represent the elastic behavior of A36 steel. All elements within the model were meshed to achieve uniform element sizes such that the size of most elements was approximately 0.4 in. x 0.4 in, except for the ground which was meshed with approximately 2-in. x 2-in. square elements. The element mesh for the ground, PCB, and connection hardware is shown in Figure 21.

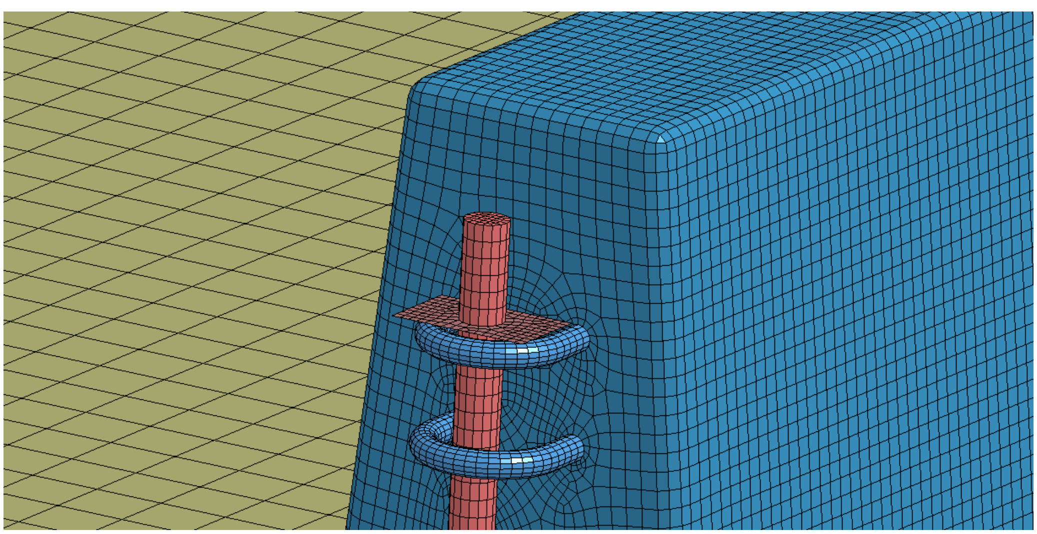


Figure 21. Element Mesh in Baseline F-Shape Model, Ground, PCB, and Connection Hardware

Contact between the ground, barrier segments, and other barrier connection hardware was defined using Automatic-Single-Surface contact. Since friction between the barrier and ground is one of the mechanisms through which PCB systems resist impact, an accurate representation of friction was necessary. A previous study at TTI measured the kinematic friction coefficient for a concrete PCB segment sliding on a concrete surface to be 0.40 [12]. This value was assigned to the contact between the ground and the barrier segments within the model. The default friction coefficient for the contact between other parts, including the pins, pin plates, and loops, was assigned a value of 0.1 for both static and dynamic friction.

Contact between the barrier and the vehicle was also defined using Automatic-Single-Surface contact but assigned coefficients of 0.2 for static friction and 0.15 for dynamic friction. These values were the original values built into the vehicle model when the F-shape PCB model was being developed. Since the development of the F-shape PCB model, several newer versions of the vehicle model have been developed with slightly lower barrier-to-vehicle friction coefficients of 0.1 for both static and dynamic friction. These newer and lower friction values were not used for this study in order to maintain a direct comparison between the simulated performance of the baseline F-shape PCB model and the PCB design concept models that were to be created during this effort. Once a concept would be selected for further investigation and development in a future research project funded by the Midwest pooled Fund Program, then a newer Dodge Ram vehicle model with the updated friction values was to be used for future simulations. The use of a Dodge Ram vehicle model with updated friction values would be used to better represent any full-scale crash testing completed using a Dodge Ram due to vehicle availability.

To avoid initial penetrations between the parts in the model, all barrier parts were placed with vertical gaps of 4 x 10^{-5} in. above the ground so parts would fall and initiate contact upon landing. This selection introduced vibration caused by the impact between the rigid ground and the rigid barrier segments, so damping was applied to the barriers for a short time until the contact forces normalized at the expected values of the barrier weights. Barrier damping was then turned off just prior to vehicle impact so it would not affect the barrier's safety performance or displacement.

This baseline model was used to simulate MASH TL-3 test designation no. 3-11, which consists of a 2270P vehicle impacting the barrier 51.2 in. upstream from the joint between segments no. 8 and no. 9 at an angle of 25 degrees and a speed of 62 mph. The vehicle model used was Version 3 of the Chevrolet Silverado model developed by the National Crash Analysis Center (NCAC) and modified by MwRSF for use in roadside safety applications. Consequently, each of the PCB concepts was simulated under the same conditions.

Validation of the Midwest F-shape PCB model was completed during a previous research effort using full-scale testing data reported in MwRSF report no. TRP-03-174-06 [13]. Crash test no. 2214TB-2 conducted as part of the report used a 2270P vehicle impacting the barrier system at a speed of 61.9 mph and at an angle of 25.4 degrees. The results of crash test no. 2214TB-2 are compared with the simulation results in Table 1.

Table 1. Comparison of Full-Scale Crash Test No. 2214TB-2 and Simulation Results

Evaluation Criteria		**Test No. 2214TB-2**	**Simulation Results**
OIV ft/s	**Longitudinal**	17.00	17.29
	Lateral	17.28	17.81
ORA g's	**Longitudinal**	7.17	7.58
	Lateral	11.37	12.70
Maximum Lateral Dynamic Barrier Deflection in.		79.65	79.51

4.2 Development of PCB Concept Models

The models for the selected PCB concepts were created in succession from concept no. 1 to concept no. 19. This process prevented any issues found during the first steps of modeling one concept from carrying over to another. Systematic construction of concept models and a shared numbering system also added to the ease with which models could be replicated to other concepts and shared issues could be identified and corrected quickly across the models.

Element types and material models used across each model are provided in Table 2. Note that certain parts were not included in all concepts. For example, part nos. 44, 45, 46, and 47 were only used in the model for concept no. 18. Barrier parts for each concept are shown in figures in the following subsections.

Table 2. Barrier Model Parts, Elements, and Materials

Part Description	Simulation Part No.	Element Type	Material
Concrete Barrier Segments	1-33	Type 2 Shell†	*MAT_RIGID
Connection Pins	40	Type 1 Solid	*MAT_PIECEWISE LINEAR_PLASTICITY
Connection Plates	41	Type 1 Solid	*MAT_PIECEWISE LINEAR_PLASTICITY
Barrier Feet	42	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Barrier Feet Bolts	43	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Connection Tubes	44	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Barrier Tubes	45	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Barrier Side Plates	46	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Barrier End Plates	47	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Connection Pin Plates	48	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Barrier Feet Side Plates	49	Type 2 Shell	*MAT_PIECEWISE LINEAR_PLASTICITY
Ground	50	Type 2 Shell	*MAT_RIGID

†In concept no. 18, the concrete ballast was modeled using solid elements.

4.2.1 Concept No. 1

Concept No. 1 consisted of PCB segments that were 12.5 ft long, 32 in. tall, and 16 in. wide at the base, with a near-vertical face that was sloped at 2.4 degrees to aid form release during construction. The barrier segments were connected with four 1¼-in. diameter steel pins inserted through the ends of the barrier segments and two steel plates that were ¾ in. thick. A single barrier segment including connection hardware weighed approximately 5,980 lb or 480 lb/ft.

The model for concept no. 1 used the baseline F-shape PCB model as a guide. Each concrete barrier segment was modeled using Belytschko-Tsay shell elements with a rigid material model, and all were assigned mass and moment of inertias, as calculated in a 3D-CAD model. The use of a rigid material to model concrete was based on the expectation of no significant damage to the concrete. The sixteen barrier segments were assigned separate part numbers from 1 to 16, with barrier no. 1 at the upstream end of the model and barrier no. 16 at the downstream end. The ground (part no. 50) was also modeled using shell elements with a rigid material model, similar to the concrete barrier segments. However, the rigid shell representing the ground was held fixed in place and thus, acted as a rigid wall. The element mesh for the connection hardware and barrier segments is shown in Figure 22.

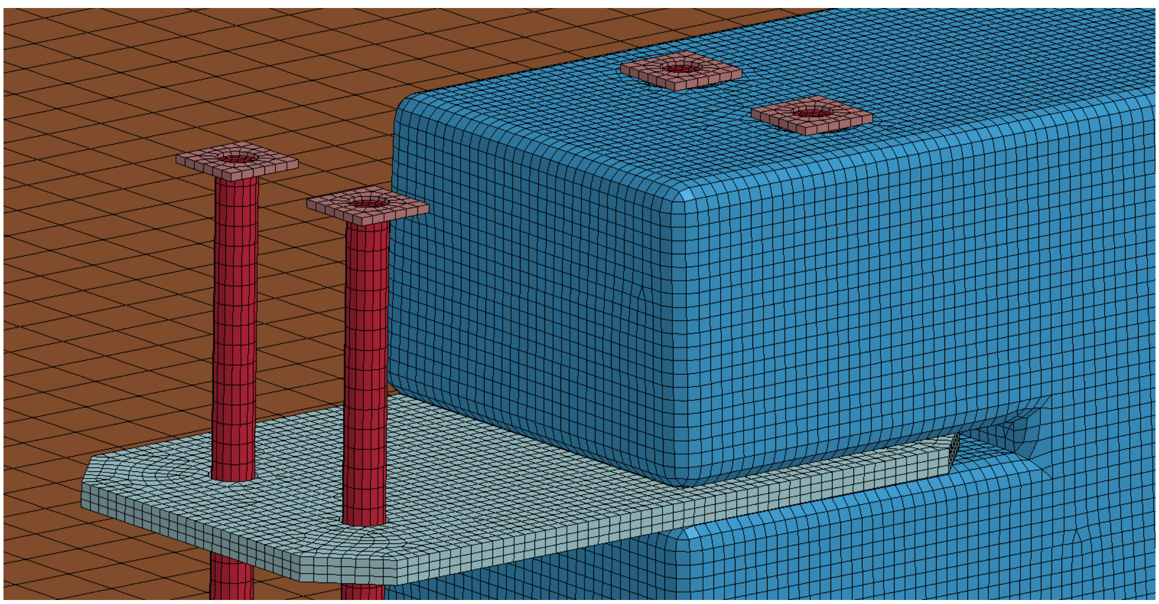
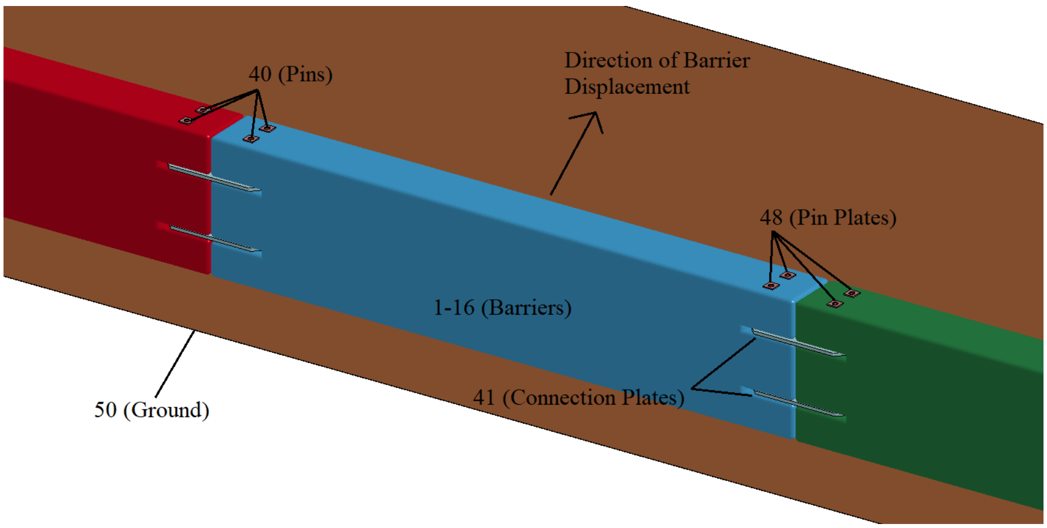
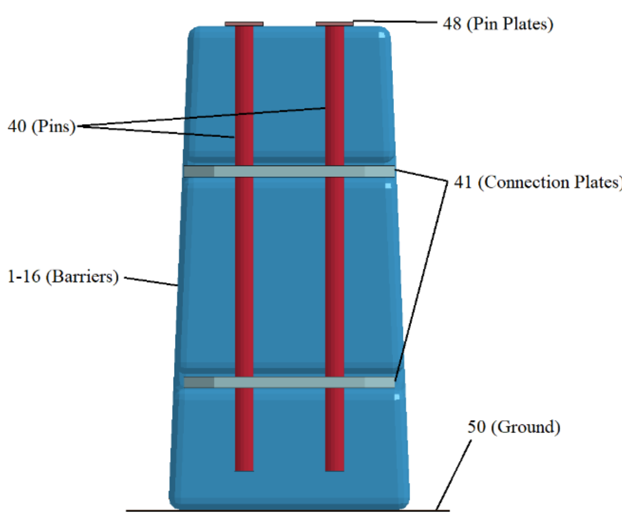


Figure 22. Mesh for Concept No. 1

The steel plates (part no. 40) and the connection pins (part no. 41) used in the joints between barriers were modeled using fully-integrated solid elements. Originally, the steel plates (part no. 48) welded to the top of the connection pins were modeled with solid elements and connected to the shaft of the connection pins using constrained nodal rigid bodies to represent the welds. However, this modeling strategy caused instability issues in early simulations, so the steel pin plates were changed to shell elements, and the constrained nodal rigid bodies were removed. The weld between the shaft and the plate of the connection pin was represented by merging the nodes between the two parts, which creates behavior similar to a weld without failure. Barrier parts used in the model for concept no. 1 are shown with labels in Figure 23.



Isometric View



Joint Section View

Figure 23. Concept No. 1 Parts - Isometric View (Top) and Section View (Bottom)

4.2.2 Concept No. 2

Once stable models of concept no. 1 were created, concept no. 2 was modeled using the same process, implementing stability fixes from later revisions of concept no. 1. Concept no. 2 was nearly identical to concept no. 1, however, concept no. 2 incorporated a reduced width – and therefore a reduced segment weight – with the addition of six feet brackets on each barrier segment. The width of the barriers was reduced from 16 in. to 11 in. at the base, with the same vertical slope of 2.4 degrees. When the steel feet on either side of the barrier were included, the total width was 19.15 in. The weight of a single barrier segment was approximately 4,260 lb, or 340 lb/ft, which was a reduction of about 71 percent compared to concept no. 1. The purpose of the steel feet was to provide stability for the barrier with reduced width while adding an easy location for anchoring the barrier, should it be desired in the future. The steel feet were modeled using shell elements and the same material properties as the other steel parts in the model. Bolt holes in the feet were modeled so that the mesh would not need to be adjusted to investigate anchorage in the future. The feet brackets were attached to the barrier segments by moving the elements where the holes were located on the vertical face of the feet to the attached barrier part. The feet brackets were not anchored to the ground in the simulation, but this could have been achieved in a similar manner. A simplified anchorage representation would have been created by moving the elements where the holes were located on the horizontal face, shown in yellow in Figure 24, to the ground part ID. Since the barrier segments were modeled with a rigid material definition, this method of connection was considered adequate for keeping the feet attached to the barrier. A view of the mesh of the steel feet brackets is shown in Figure 24.

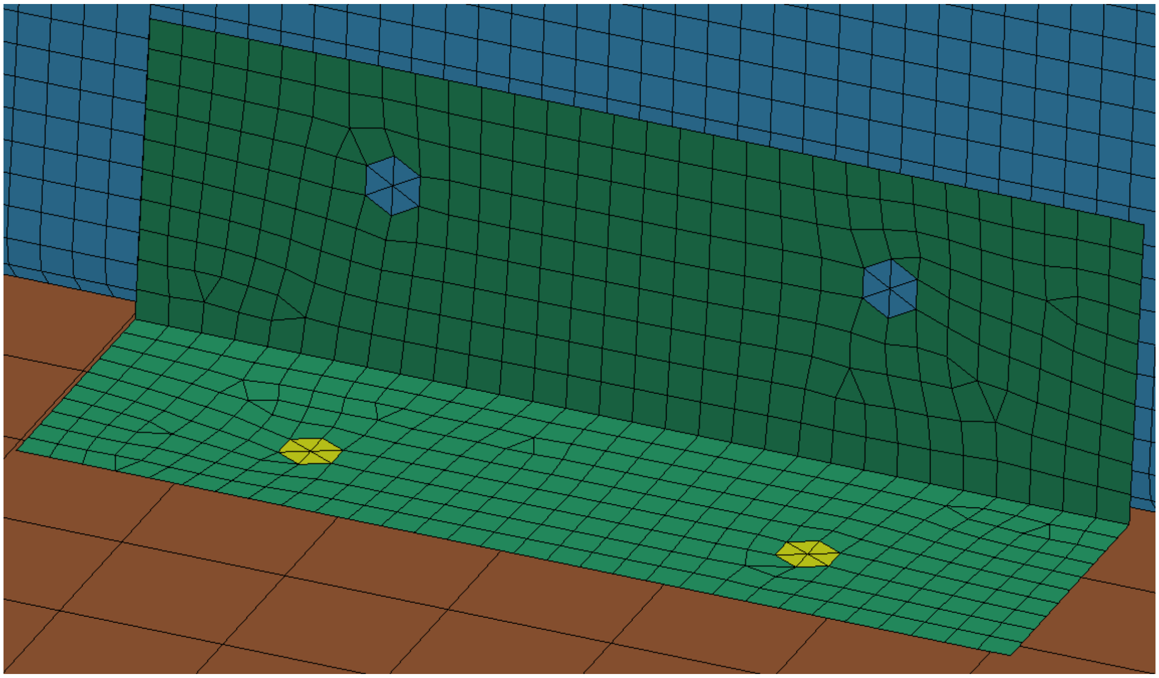


Figure 24. Mesh of Steel Feet Brackets for Concept No. 2

The original design for concept no. 2 used a single connection pin on either side of the joint between barriers, for a total of two connection pins per joint. Preliminary simulations with this pin clearly showed that the use of two pins per joint was not sufficient to maintain continuity between barrier segments. The discontinuity at the joint directly downstream from the impact point during the initial simulation is shown in Figure 25. Note that the pickup model has been hidden so that the translation of the barriers is more easily visible.

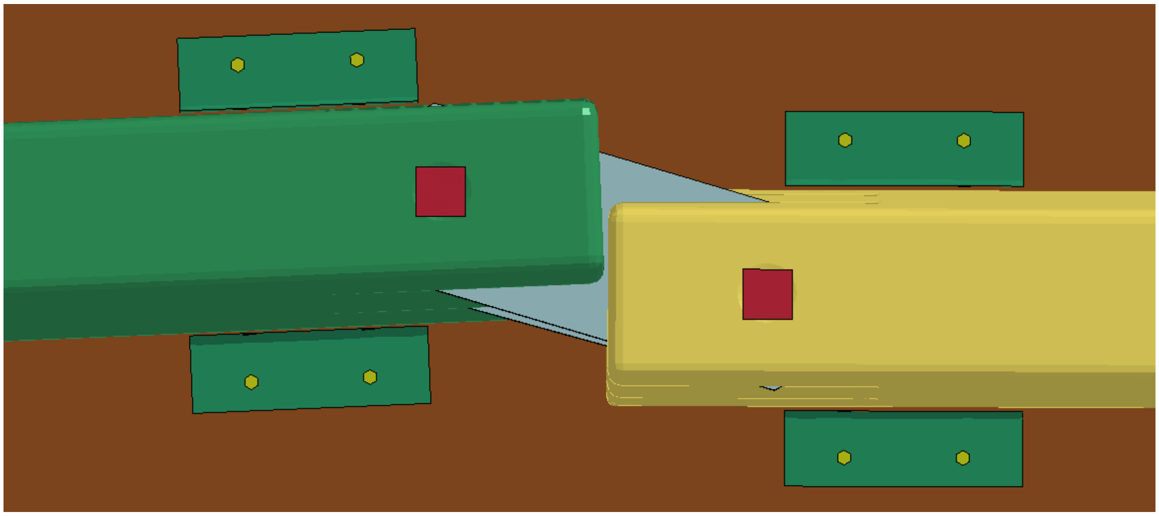
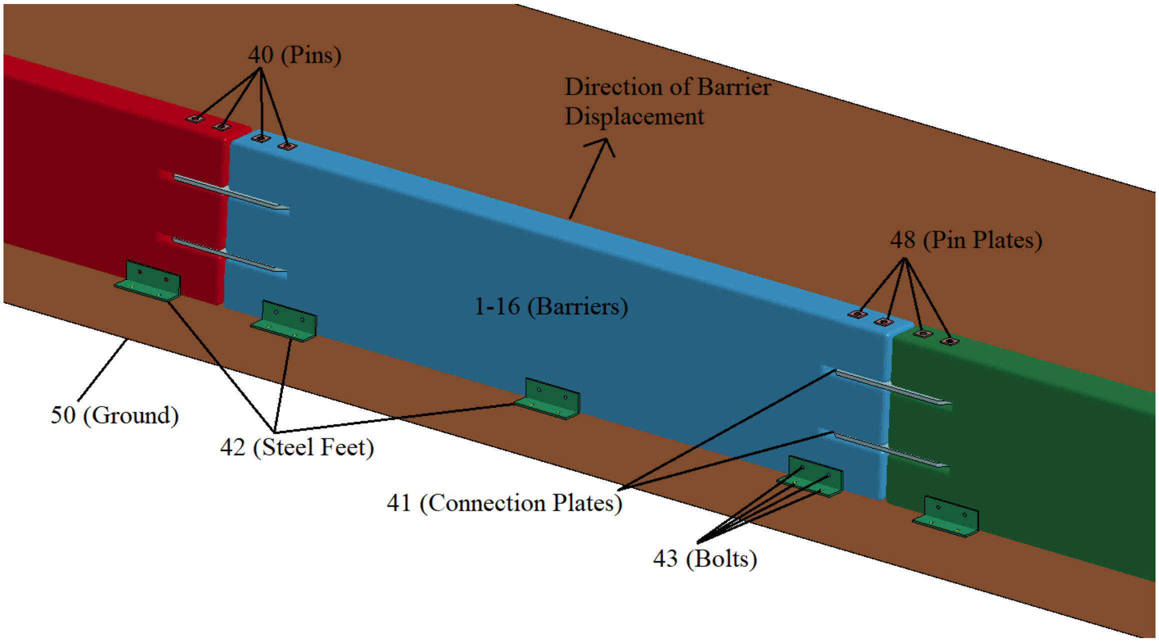
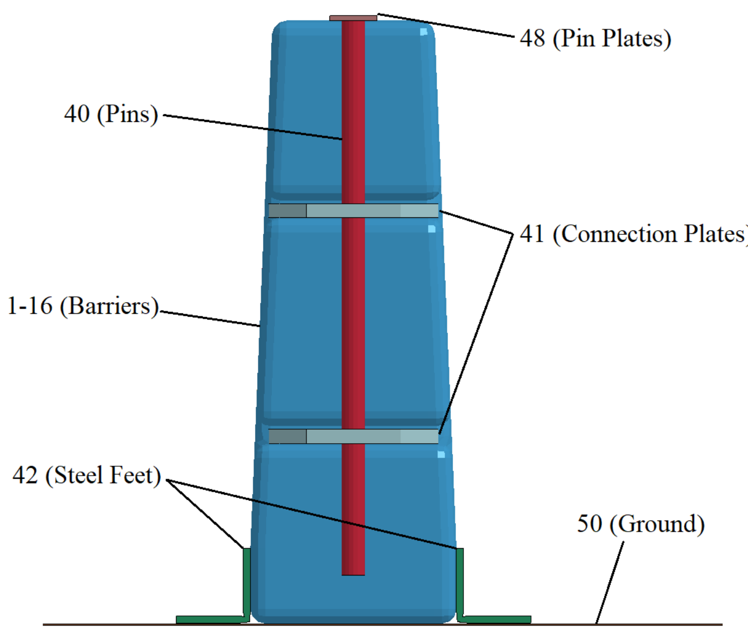


Figure 25. Discontinuity Issue with Original Connection Design of Concept No. 2

To address the discontinuity, a second connection pin was added on either side of the joint, for a total of four pins per joint. Adding a second pin resulted in a joint design that was very similar to concept no. 1; however, the arrangement of the connection pins was in a longitudinal orientation instead of a lateral orientation, as in concept no. 1. This adjustment was required because the pins would not have adequate clearance in a lateral orientation with the reduced barrier width. The adjusted pin arrangement, as well as the labelled barrier parts in the model for concept no. 2, are shown in Figure 26.



Isometric View



Joint Section View

Figure 26. Concept No. 2 Parts - Isometric View (Top) and Section View (Bottom)

4.2.3 Concept No. 17

Concept no. 17 featured similar geometry to concept no. 2, with the primary difference in the connection design. In concept no. 17, barrier segments sat within steel feet brackets to transfer forces from impact to adjacent barrier segments and the pins and pin plates were removed. The concrete barrier segments were 11 in. wide, but the feet brackets increased the total width to 19.25 in. Each barrier segment weighed approximately 4,430 lb, or 350 lb/ft, including connection hardware. Since the concrete barrier segments sat on top of the steel feet, the overall height was 32.5 in., which was 0.5 in. higher than the other concepts.

Creating the barrier model for concept no. 17 followed the same process as concepts no. 1 and no. 2, but concept no. 17 only consisted of the concrete barrier segments and steel feet brackets located at each joint. Both the barrier segments and feet were modeled with shell elements similar to previous design concepts. The only major adjustment made for this concept was the contact friction between the ground, steel feet, and barrier segments. Previously, the barrier segments were in contact with the ground. For concept no. 17, friction was defined between the barrier segments and the steel feet, and then the steel feet and the ground. Both interactions were assigned static and dynamic coefficients of 0.4 to remain consistent with the other PCB concepts.

Similar to concept no. 2, concept no. 17 experienced continuity issues between barrier segments. Analysis of the preliminary simulation found that the steel feet bracket was not tall or strong enough to prevent the top of the barrier segments from tilting back upon impact and creating a snag opportunity on the adjacent downstream segment. This discontinuity issue is shown in Figure 27, where the pickup model has been hidden. The element mesh is shown to help illustrate that the upstream barrier on the left tilted back due to vehicle impact, while the downstream barrier on the right tilted forwards due to inertia as the feet bracket pushed the bottom of the barrier back.

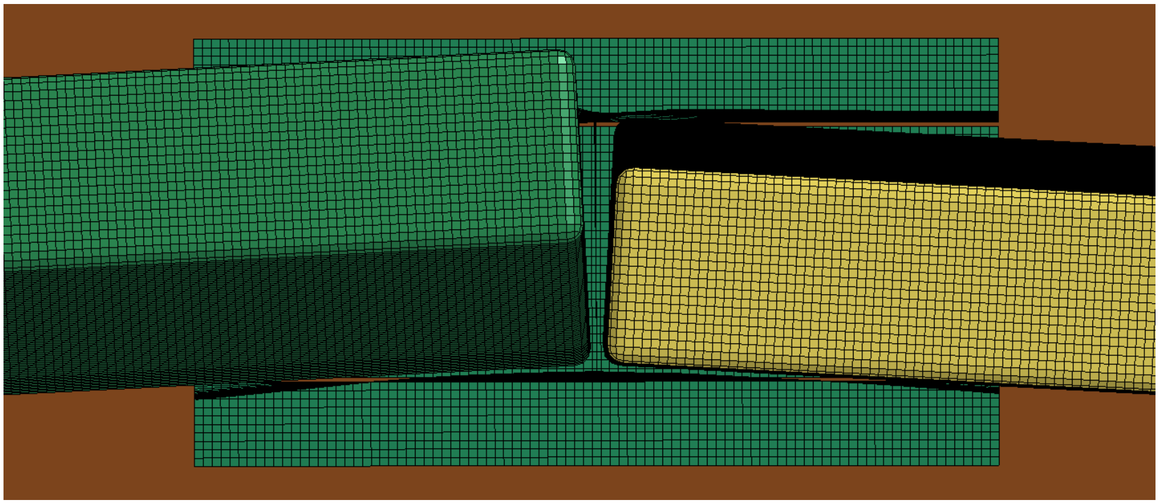
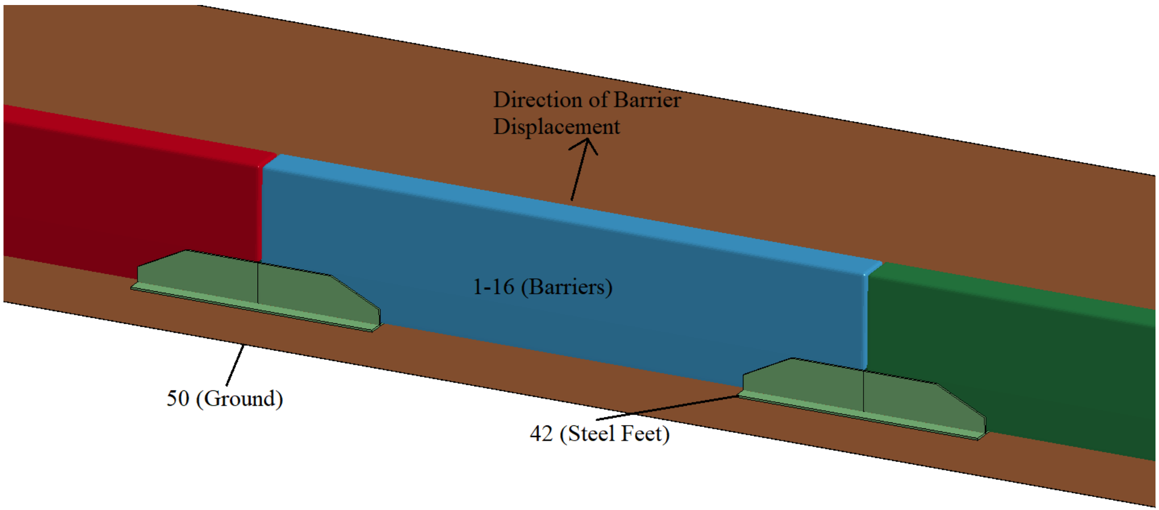


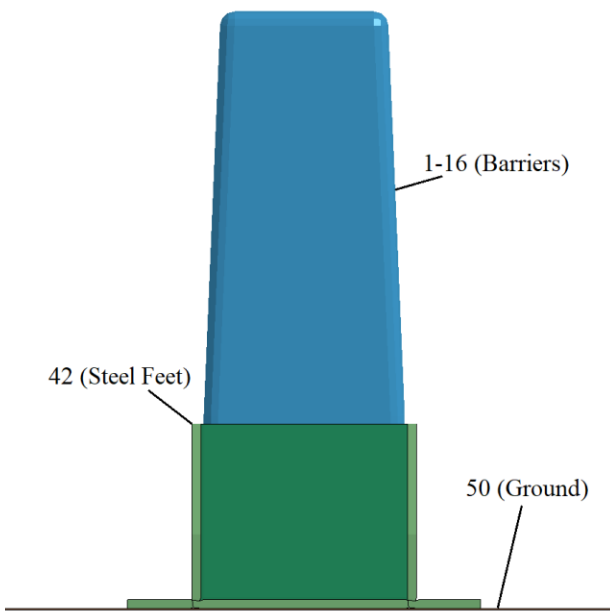
Figure 27. Discontinuity Issue with Original Feet Brackets in Concept No. 17

The changes implemented to the connection design to alleviate the continuity issues consisted of a new feet bracket design. The new steel feet were 60 in. long, 19.25 in. wide, 10 in. tall, and would be built up from welded plates that were ½ in. thick, except for the vertical center plate which was ⅜ in. thick. These new measurements were a large increase from the original feet, which were 36 in. long, 19.25 in. wide, 6 in. tall, and made up of L6x4x⅜ steel angles welded to ⅜-in. thick plates. The welded plates were modeled by merging nodes along shared edges to replicate the weld behavior.

Simulations with the larger steel feet still demonstrated some amount of discontinuity that was enough to snag the vehicle and terminate the simulations, but it was found that moving the impact point farther upstream to the upstream quarter point of the barrier segment, approximately 61.3 in. upstream from the original impact location did not cause the simulation to terminate. Although this different impact location would not result in truly direct comparison, the simulation with impact at this location was used for comparison to the other PCB concepts. It was determined that this concept would need significant modification to create a viable design, so no further investigation was conducted. The barrier parts for concept no. 17 are labelled in Figure 28.



Isometric View

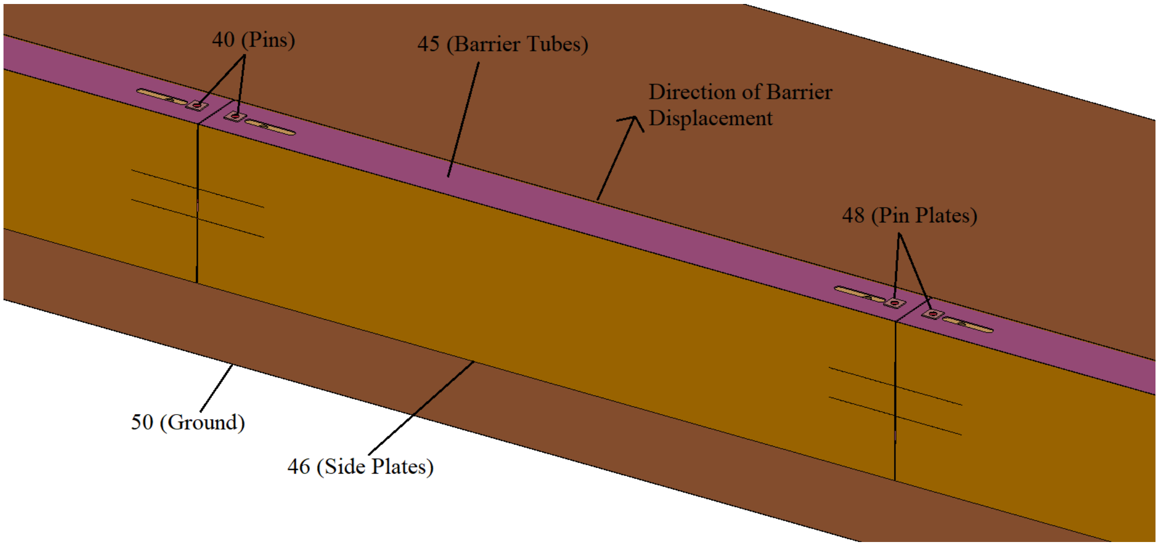


Joint Section View

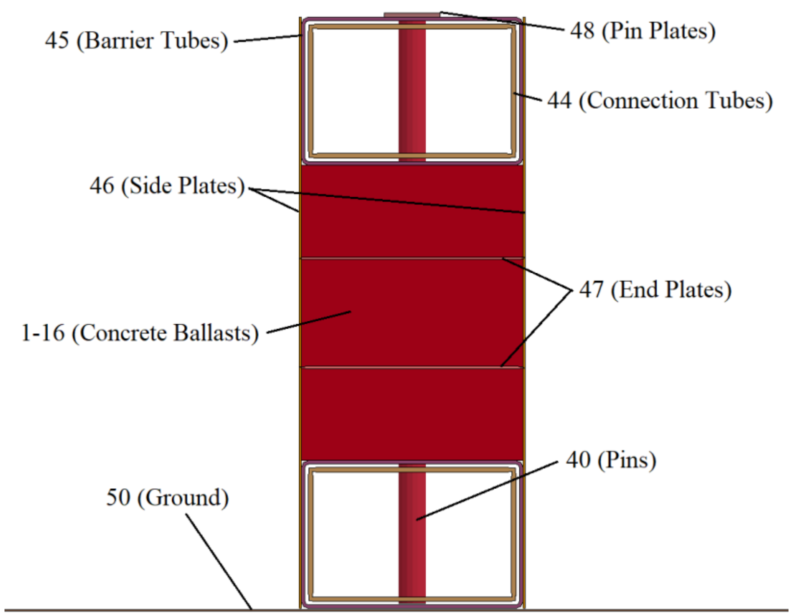
Figure 28. Concept No. 17 Parts- Isometric View (Top) and Section View (Bottom)

4.2.4 Concept No. 18

Concept no. 18 was unlike the other previous PCB concepts, such that it consisted of barrier segments with vertical faces and used steel as the primary material. Concept No. 18 consisted of two steel plates and two rectangular HSS tubes encasing a concrete ballast that was kept in place by small steel plates at either end of the barrier segment. The segments were connected using rectangular HSS tubes that nested inside the HSS at the top and bottom of the barrier segments. The nested HSS tubes were connected using 1.5-in. diameter steel connection pins, similar to the 1.25-in. diameter steel pins used in the previous PCB concepts. Each barrier segment measured 12.25 in. wide, 32 in. tall, 12.5 ft long, and weighed approximately 3,140 lb, or 250 lb/ft. Concept No. 18 is shown with parts labeled in Figure 29.



Isometric View



Joint Section View

Figure 29. Concept No. 18 Parts - Isometric View (Top) and Section View (Bottom)

The method for modeling concept no. 18 needed to be slightly adjusted, since this concept represented a steel barrier design concept that was ballasted with concrete rather than a traditional concrete barrier. All the steel parts of concept no. 18 were modeled with shell elements, with the exception of the connection pins, which were modeled as solid elements. Most of the steel barrier parts that would be welded together were represented in the model by merging nodes at the weld locations. However, this was not ideal for the welds between the side plates and the barrier HSS tubes, so constrained nodal rigid bodies were used to connect these parts.

The concrete ballasts were modeled with solid elements with a rigid material definition. Solid elements were used so that damage to the concrete ballast could be investigated if necessary in later simulations without needing to adjust the model geometry. Element sizes for the concrete ballast were approximately 1.2 in. x 1.2 in., which were larger than the typical element size to save computation time added by the solid element formulation. The element mesh for the parts in concept no. 18 is shown in Figure 30, below.

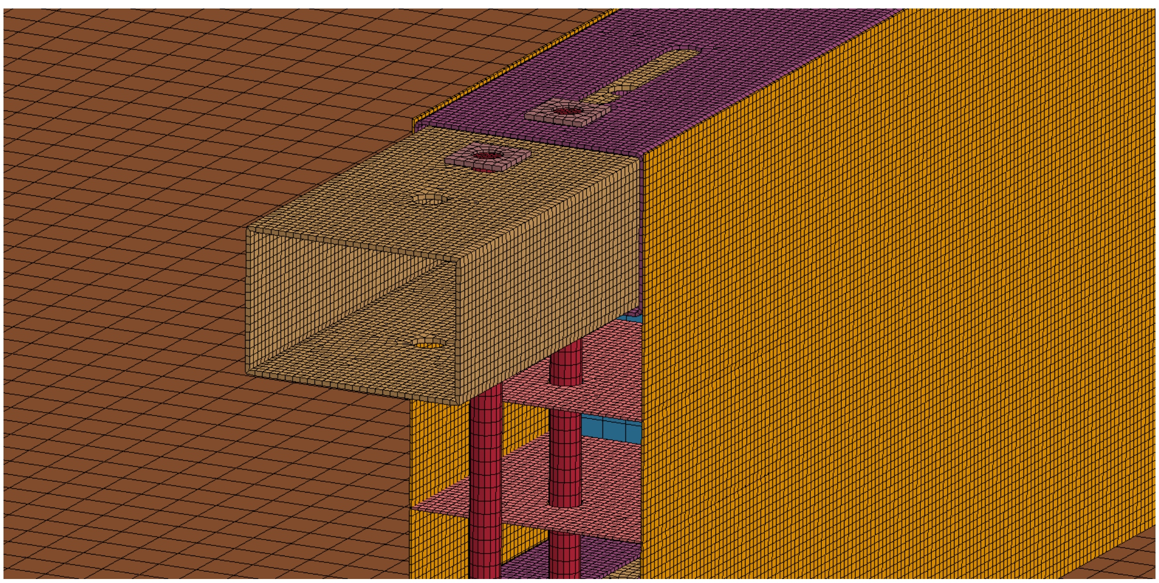
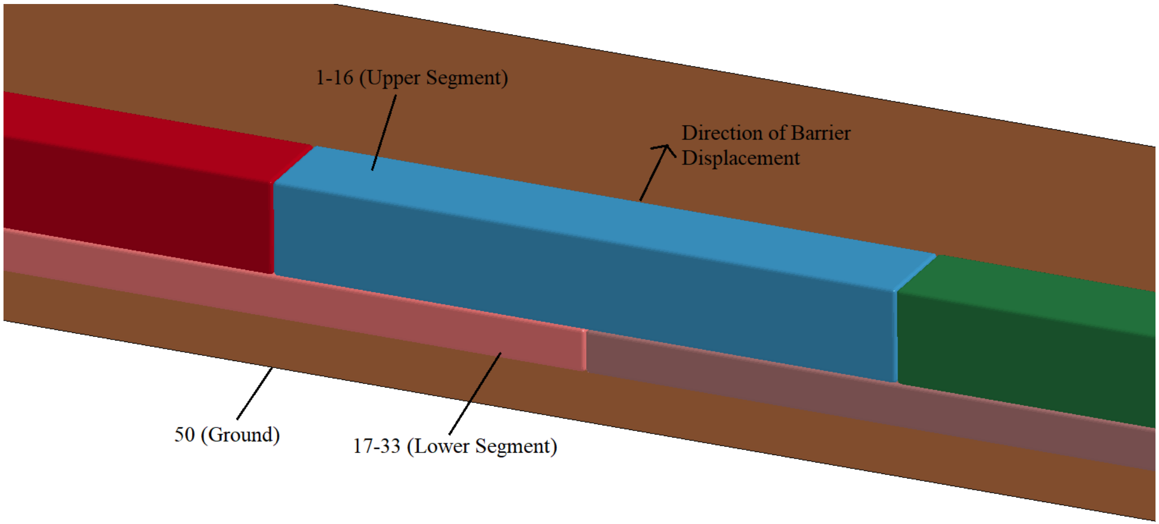


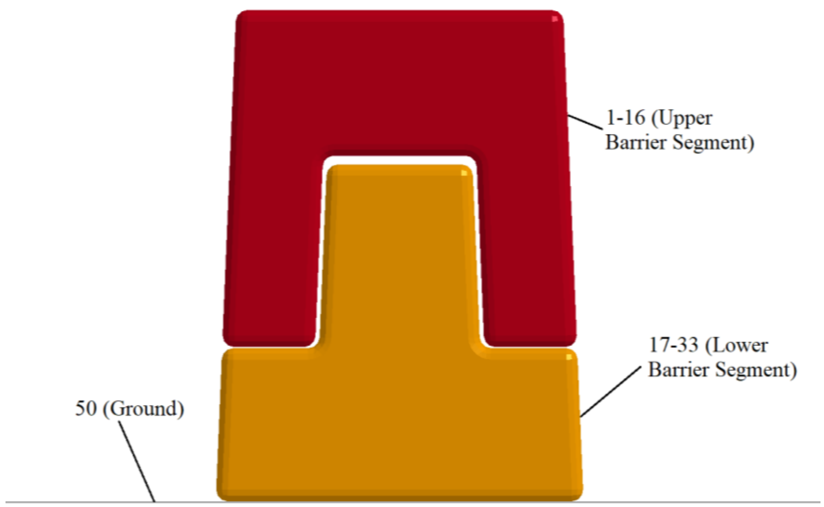
Figure 30. Mesh of Concept No. 18

4.2.5 Concept No. 19

Concept no. 19 consisted of staggered halves of PCB segments that interlocked when stacked on top of each other. The bottom half of the barrier was shaped like an inverted T, and the top half was shaped like an inverted U. When the top halves were stacked on top and staggered at half of the length of the barrier segments, the segments interlocked and created a very strong connection with excellent continuity. The first version of concept no. 19 measured 24 in. wide and 32 in. tall when the barrier segments were stacked as they would be during installation. The bottom half of the barrier segments weighed approximately 4,500 lb, and the top half weighed approximately 4,450 lb, for a total weight of 8,950 lb, or 716 lb/ft. The labeled parts for the concept no. 19 model are shown in Figure 31.



Isometric View



Joint Section View

Figure 31. Concept No. 19 Parts- Isometric View (Top) and Section View (Bottom)

Since concept no. 19 does not require any connection hardware and solely consists of the two barrier halves, the model for this concept was very straightforward. The concrete barrier halves were modeled using rigid shell elements and then assigned mass and moments of inertia, similar to the other models. The contact between the PCB sections and the ground was defined with Automatic-Single-Surface contact, which was also used to define the contact at the interface between individual barrier sections. Element sizes were meshed to be approximately 0.4 in. x 0.4 in. for the concrete barrier segments, which can be seen relative to the model parts labeled in Figure 32.

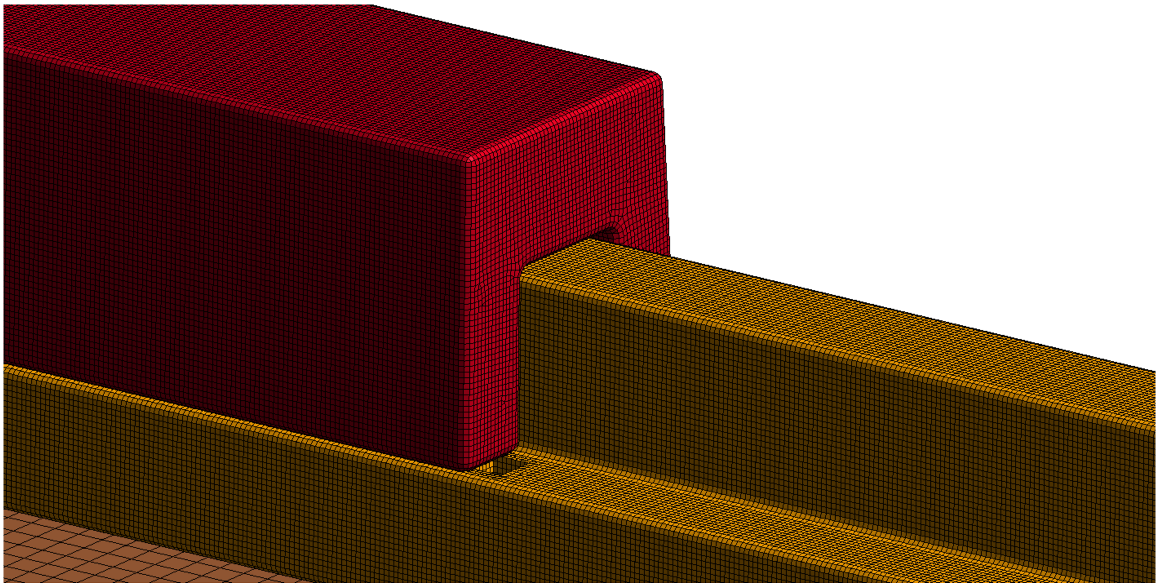


Figure 32. Meshed View of Concept No. 19

4.2.6 Concept No. 16

After discussing preliminary simulation results from concept nos. 1, 2, 17, 18, and 19, the research team decided to investigate a sixth design concept that shared features of the concepts that performed well. That design, concept no. 16, consisted of staggered concrete blocks, similar to concept no. 19, except instead of using interlocking shapes, concept no. 16 used drop-pins to connect the barrier segments at each end and the midpoints. When looking at the barrier cross section end-on, the faces of the barrier had a slight hourglass shape to prevent vehicle climb. This design also allowed for a single casting shape for the barrier segments that could be installed either on the top or the bottom and was not restrictive with segment orientation. The first version of concept no.

16 measured 18 in. wide and 32 in. tall when the barrier segments were stacked as they would be during installation. Each of the barrier segments weighed approximately 3,575 lb, for an installed linear weight of 576 lb/ft. The labeled parts for concept no. 16 are shown in Figure 33.

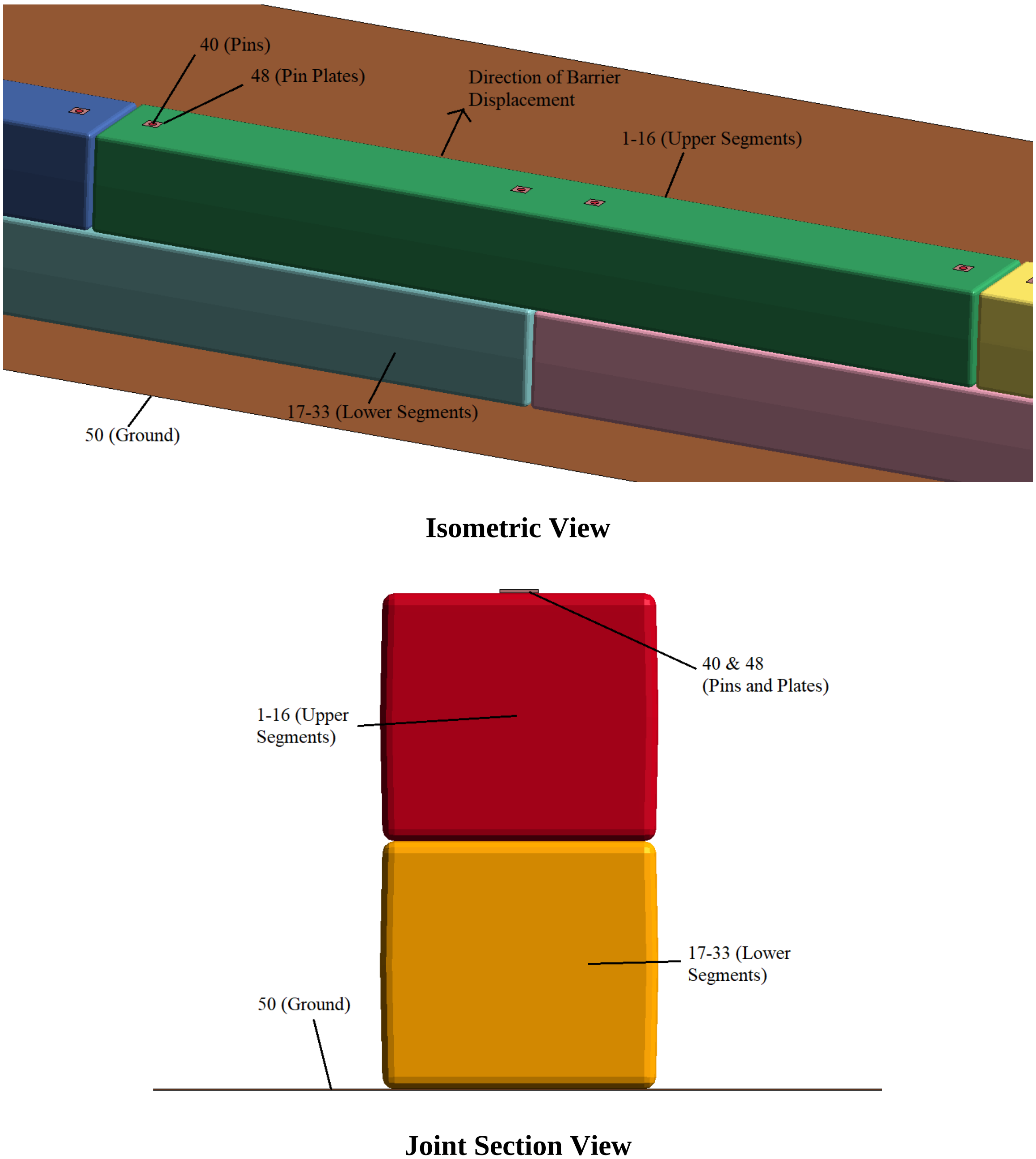


Figure 33. Concept No. 16 Parts - Isometric View (Top) and Section View (Bottom)

The model for concept no. 16 used similar techniques to concept nos. 1 and 19. The concrete barrier segments were modeled with rigid shells elements and then assigned mass and moments of inertia calculated using 3D-CAD software. The drop-pins were modeled using deformable solid elements for the shaft and shell elements for the pin plate similar to concept no. 1. Contact in the model used the Automatic-Single-Surface definition, and the element sizes were kept consistent with previous concept simulations. A view of the mesh used for concept no. 16 is shown in Figure 34.

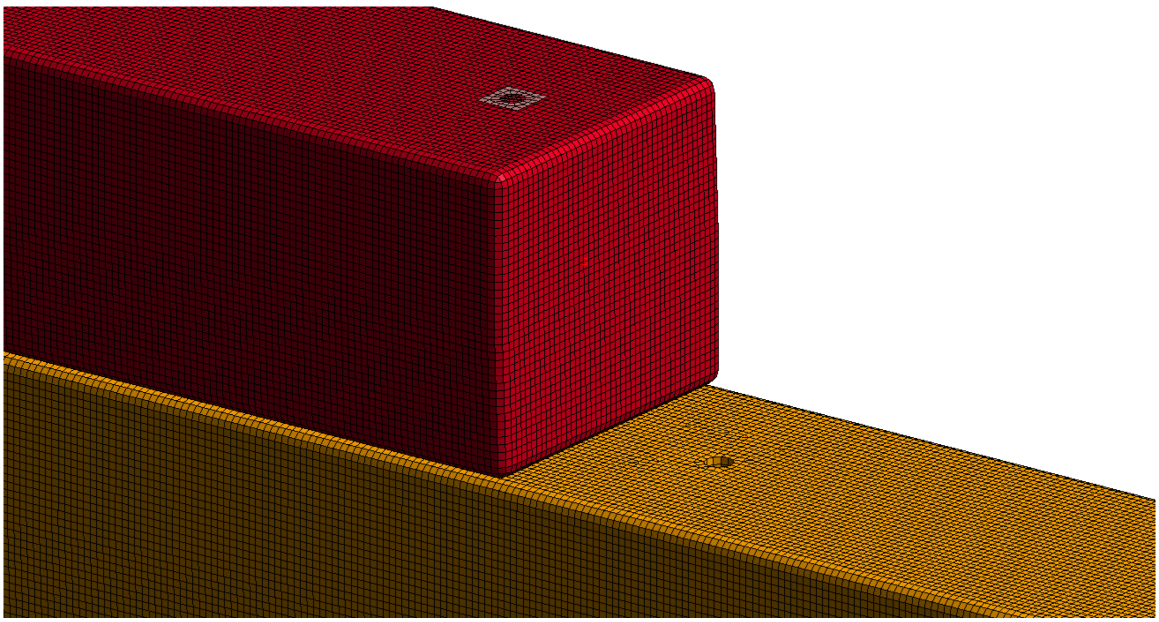


Figure 34. Meshed View of Concept No. 16

4.3 LS-DYNA Simulation Results

Multiple simulations were run for each design concept so that modeling errors and issues could be corrected and to investigate slight modifications to each concept. Each simulation was conducted to match MASH test designation no. 3-11 using a modified Chevrolet Silverado model impacting the PCB system at a speed of 62 mph and at an angle of 25 degrees. Each of the PCB concepts was modeled with an installation length of roughly 200 ft or sixteen 12.5-ft long barriers. For most concepts, the impact point was 51.2 in. upstream from the central PCB joint similar to the baseline model, and for concepts with staggered segments, the impact point was 51.2 in. upstream from the central joint in the upper segments.

4.3.1 Baseline F-Shape Results

The F-Shape PCB model that was used as a baseline for comparison to the PCB design concepts was validated with full-scale crash testing under previous research efforts [11]. This F-shape barrier used 12.5-ft. long segments that measure 22.5 in. wide by 32 in. tall and had a linear weight of approximately 400 lb/ft. The barrier cross section is shown in Figure 35, and barrier data is tabulated in Table 3. Although previous simulation results existed from the 2007 research, the simulation was conducted again to verify that the model still behaved accurately with updated computer hardware and software. The new simulation behaved as expected, and the results of the MASH test designation no. 3-11 simulations are tabulated below in Table 4, while sequential images from the simulation are shown in Figure 36.

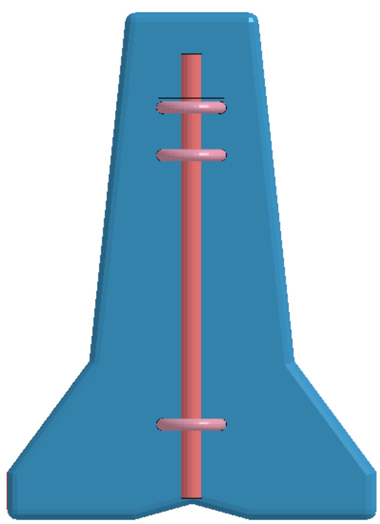


Figure 35. Cross Section of F-Shape PCB

Table 3. Baseline F-Shape Barrier Data

Barrier Data	
Height (in.)	15.8
Width (in.)	20.2
Segment Length (ft)	16.9
Total Segment Weight (lb)	4,986
Linear Weight (lb/ft)	399
Connection Type	Pin & Hook

Table 4. Baseline F-Shape Simulation Results

Evaluation Criteria		Simulation Results
Max. Vehicle Roll (deg.)		15.8
Max. Vehicle Pitch (deg.)		20.2
Max. Bumper Climb (in.)		16.9
OIV (ft/s)	**Longitudinal**	17.3
	Lateral	17.8
ORA (g's)	**Longitudinal**	7.6
	Lateral	12.7
Barrier Knee Angle (deg.)		22.6
Maximum Lateral Dynamic Barrier Deflection (in.)		79.5

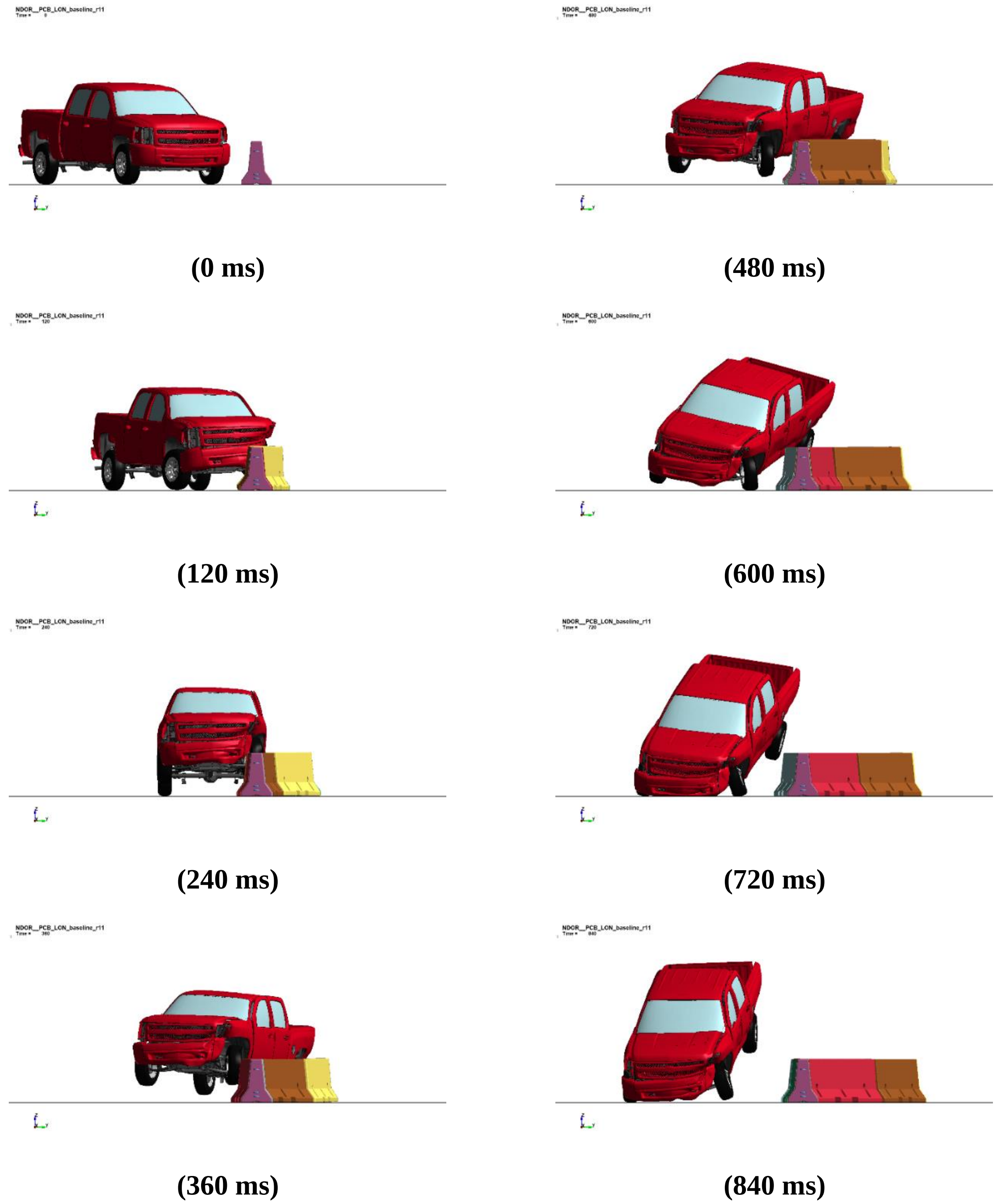


Figure 36. Sequential Images of Baseline F-Shape PCB Simulation

4.3.2 Concept No. 1 Results

The first successful simulation of concept no. 1 featured the PCB design described in the earlier section which measured 16 in. wide by 32 in. tall and had a linear weight of about 480 lb/ft. A cross section view is shown in Figure 37, and these details are tabulated in Table 5. This version of the concept was labelled concept no. 1A so that future modifications to this concept could be compared and labelled with increasing letters. Concept no. 1A had a maximum lateral barrier displacement of 35.1 in. and did not exceed any MASH safety criteria. Detailed results of concept no. 1A simulation are tabulated in Table 6 and followed by sequential images in Figure 38.

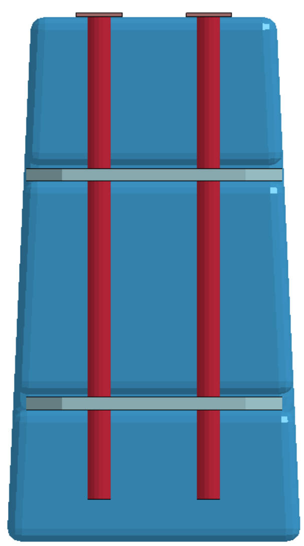


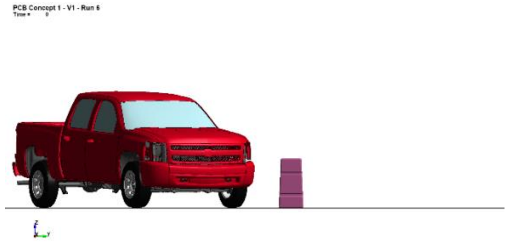
Figure 37. Cross Section of Concept No. 1A

Table 5. Concept No. 1 Barrier Data

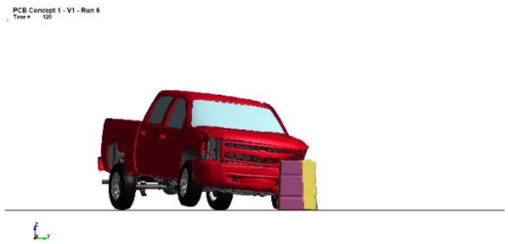
Barrier Data	
Height (in.)	32
Width (in.)	16
Segment Length (ft)	12.5
Total Segment Weight (lb)	5,982
Linear Weight (lb/ft)	479
Connection Type	Pin & Plates

Table 6. Concept No. 1 Simulation Results

Evaluation Criteria		Simulation Results
Max. Vehicle Roll (deg.)		18.1
Max. Vehicle Pitch (deg.)		4.8
Max. Bumper Climb (in.)		3.0
OIV (ft/s)	**Longitudinal**	13.9
	Lateral	19.0
ORA (g's)	**Longitudinal**	7.2
	Lateral	12.1
Barrier Knee Angle (deg.)		7.4
Maximum Lateral Dynamic Barrier Deflection (in.)		35.1



(0 ms)



(120 ms)

(240 ms)

(360 ms)

(480 ms)

(600 ms)

(720 ms)

(840 ms)

Figure 38. Sequential Images of Concept No. 1 Simulation

A modified version of concept no. 1A, labelled concept no. 1B, utilized a longitudinal pin arrangement, as shown in Figure 39 (Right), instead of a lateral pin arrangement, as shown in Figure 39 (Left). Concept no. 1B was simulated to MASH test designation no. 3-11 and the results were within roughly 5 percent error of the results of concept no. 1A, so the pin arrangement was determined to be insignificant to barrier safety performance. The results of concept nos. 1A and 1B are compared in Table 7.

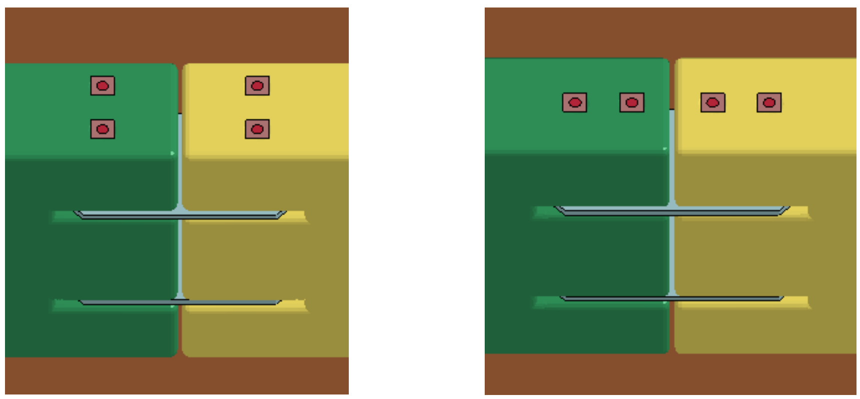


Figure 39. Concept No. 1A (Left) and Concept No. 1B (Right) Pin Arrangements

Table 7. Comparison of Pin Arrangement Simulation Results for Concept No. 1

Evaluation Criteria		**Lateral Pins (1A)**	**Longitudinal Pins (1B)**
Max. Vehicle Roll (deg.)		18.1	19.3
Max. Vehicle Pitch (deg.)		4.8	4.8
Max. Bumper Climb (in.)		3.0	2.9
OIV (ft/s)	**Longitudinal**	13.9	13.2
	Lateral	19.0	18.8
ORA (g's)	**Longitudinal**	7.2	6.9
	Lateral	12.1	12.6
Barrier Knee Angle (deg.)		7.4	7.8
Maximum Lateral Dynamic Barrier Deflection (in.)		35.1	36.2

Overall, both versions of concept no. 1 resulted in acceptable safety criteria. Concept No. 1A had a lower maximum lateral barrier deflection of 35 in., which was below the design criteria of 36 in. The performance of the two versions of concept no. 1 was nearly identical. However, the concept no. 1A deflection was more favorable, so the decision was made to move forward with concept no. 1A with the lateral pin arrangement. Therefore, any references to the concept no. 1 design refer to the pin arrangement used in concept no. 1A. Concept No. 1 was slightly heavier than the F-shape PCB, weighing nearly 6,000 lb, which reduced barrier deflection. Since concept no. 1 performed acceptably, it was recommended as a viable design concept.

4.3.3 Concept No. 2 Results

Concept no. 2 was a barrier design similar to concept no. 1B but incorporated a slimmer segment and steel feet at the bottom of the barrier to provide stability. These changes to the design were made to keep overall barrier behavior while reducing the barrier weight. Concept no. 2 was 11 in. wide by 32 in. tall and weighed approximately 340 lb/ft. A cross section view is shown in Figure 40, and design details are provided in Table 8. Concept no. 2 resulted in acceptable MASH safety criteria, but the PCB had a maximum lateral barrier displacement of 62.9 in., which exceeded the design goal of 36 in. The complete simulation results are listed in Table 9, and the sequential images from the simulation are shown in Figure 41. Due to the excessive barrier deflection compared to the design goal and concept no. 1, concept no. 2 was not recommended as a viable design.

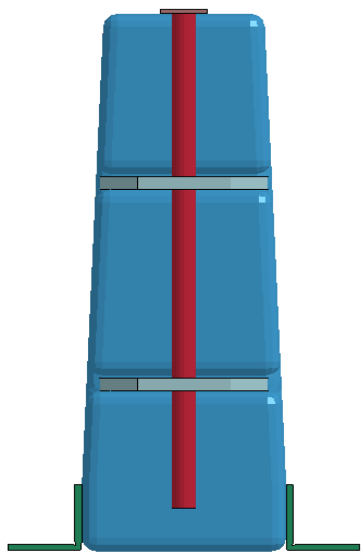


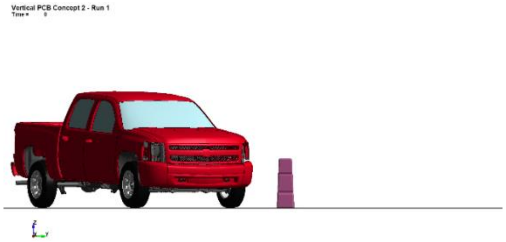
Figure 40. Cross Section of Concept No. 2

Table 8. Concept No. 2 Barrier Data

Barrier Data	
Height (in.)	32
Width (in.)	11
Segment Length (ft)	12.5
Total Segment Weight (lb)	4,256
Linear Weight (lb/ft)	340
Connection Type	Pin & Plates

Table 9. Concept No. 2 Simulation Results

Evaluation Criteria		Simulation Results
Max. Vehicle Roll (deg.)		15.0
Max. Vehicle Pitch (deg.)		6.6
Max. Bumper Climb (in.)		2.8
OIV (ft/s)	**Longitudinal**	13.4
	Lateral	18.6
ORA (g's)	**Longitudinal**	4.8
	Lateral	13.6
Barrier Knee Angle (deg.)		13.9
Maximum Lateral Dynamic Barrier Deflection (in.)		62.9



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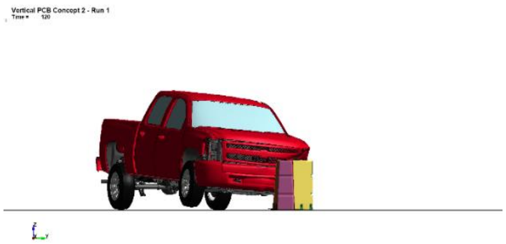

(120 ms)

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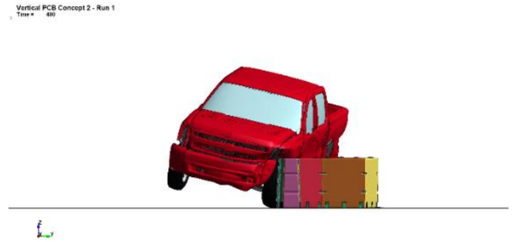


(480 ms)

(600 ms)

(720 ms)

(840 ms)

Figure 41. Sequential Images of Concept No. 2 Simulation

4.3.4 Concept No. 17 Results

Concept no. 17 consisted of barrier segments that were the same size as concept no. 2 but were set into steel feet that spanned the joint between segments. This PCB concept aimed to simplify installation and inspection. The barrier cross section is shown in Figure 42, and the dimensions and weights for concept no. 17 are listed in Table 10. This concept was slightly lighter than the F-shape PCB and was expected to be easy to reinforce and anchor.

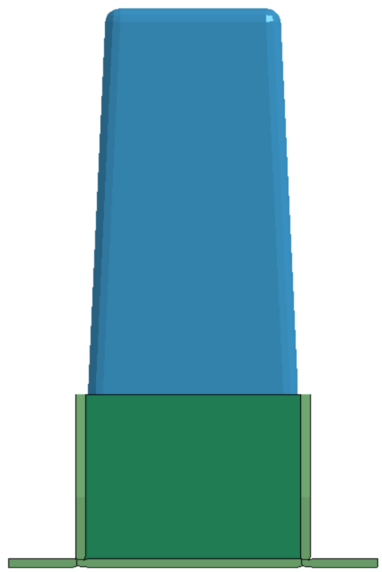


Figure 42. Cross Section of Concept No. 17

Table 10. Concept No. 17 Barrier Data

Barrier Data	
Height (in.)	32
Width (in.)	11
Segment Length (ft)	12.5
Total Segment Weight (lb)	4,428
Linear Weight (lb/ft)	354
Connection Type	Steel Feet

The first simulation for concept no. 17 terminated due to numerical instabilities caused by vehicle snag at the first joint downstream from impact. Since this concept did not have a connection that could transfer shear at the top of the barrier segments, the impacted barrier segment tipped away from impact, while the downstream segment did not tip. The uneven barrier faces presented a large discontinuity where the vehicle snagged, as shown in Figure 43.

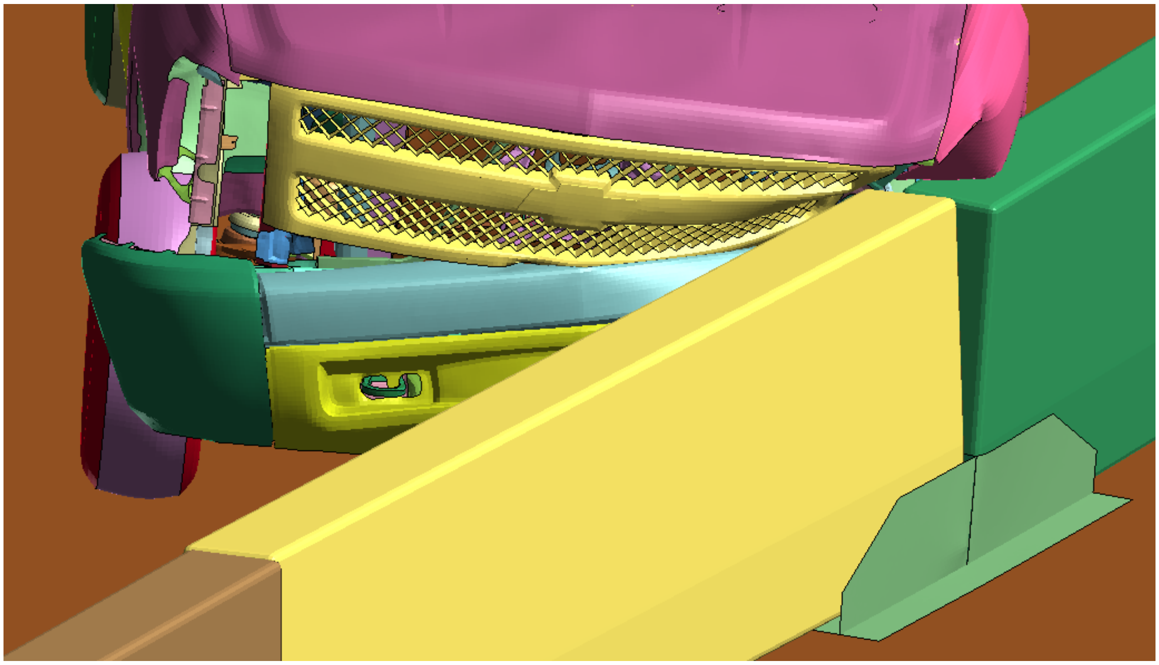


Figure 43. Concept No. 17 Snag Opportunity at Original Impact Point, 51 in. Upstream from Joint

To test the severity of this issue, concept no. 17 was simulated with impact points at approximately half of a barrier length, or 75 in. upstream from the joint. Compared to the original impact location at roughly 51 in. upstream, this location was expected to decrease the amount of vehicle snag. However, this impact location did not remove the vehicle snag, shown in Figure 44, and the simulation terminated due to numerical errors.

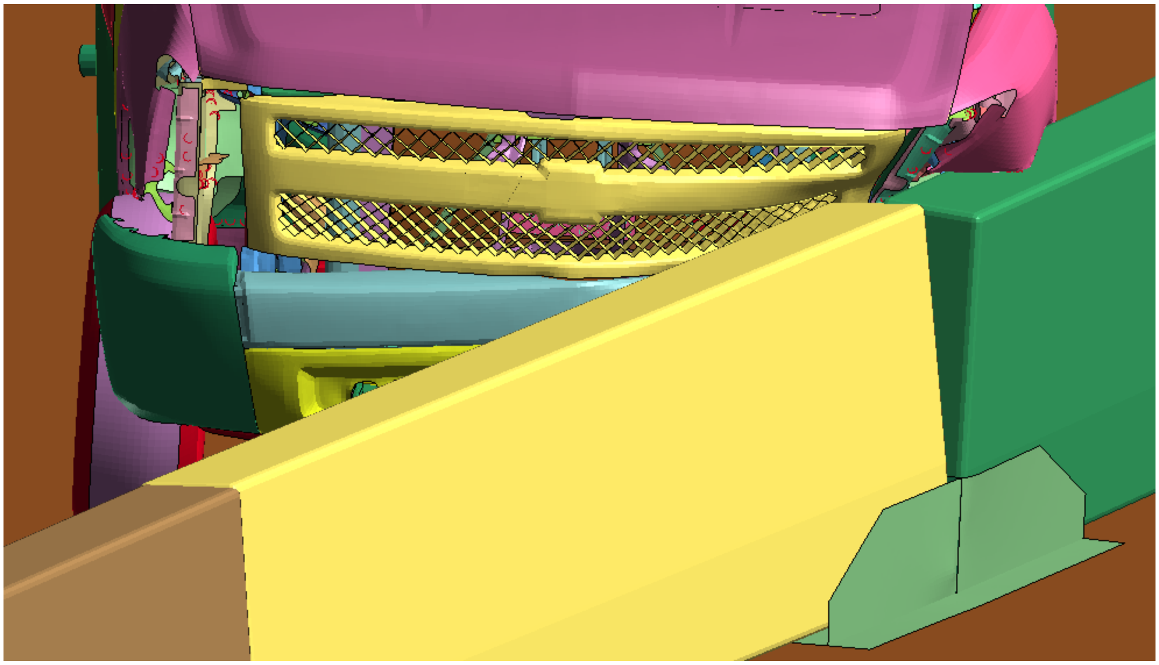
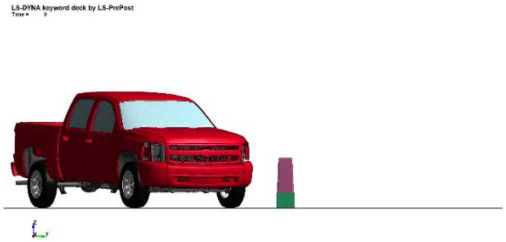


Figure 44. Concept No. 17 Snag Opportunity at 1/2-Barrier Impact Point

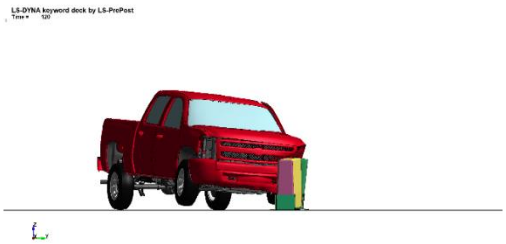
A third impact location at three quarters of a barrier length, or 112.5 in. upstream from the joint was also tested to check for vehicle snag. This impact location still created some vehicle snag due to barrier discontinuity, but the simulation did not terminate early due to errors. The safety criteria were evaluated and showed that the concept nearly reached the maximum MASH limit for lateral occupant ridedown acceleration of 20.49 g. The safety criteria and barrier deflection are listed in Table 11 and sequential images from the simulation are shown in Figure 45. Due to the barrier displacement exceeding the design goal of 36 in., and the propensity for vehicle snag indicating a need for connection improvements, concept no. 17 was not recommended as a viable design.

Table 11. Concept No. 17 Simulation Results

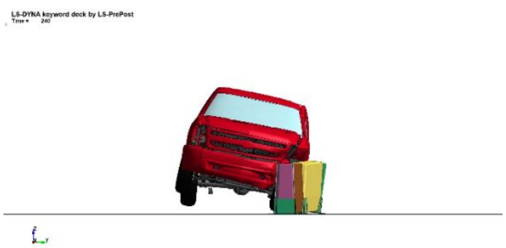
Evaluation Criteria		Simulation Results
Max. Vehicle Roll (deg.)		14.1
Max. Vehicle Pitch (deg.)		23.0
Max. Bumper Climb (*in.*)		4.2
OIV (ft/s)	**Longitudinal**	12.3
	Lateral	16.9
ORA (g's)	**Longitudinal**	6.3
	Lateral	19.0
Barrier Knee Angle (deg.)		8.7
Maximum Lateral Dynamic Barrier Deflection (in.)		57.4



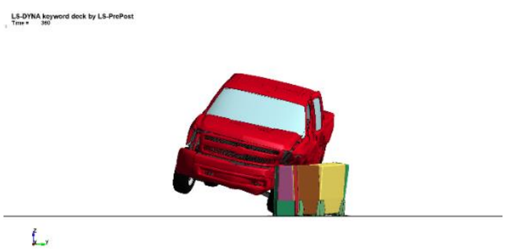
(0 ms)



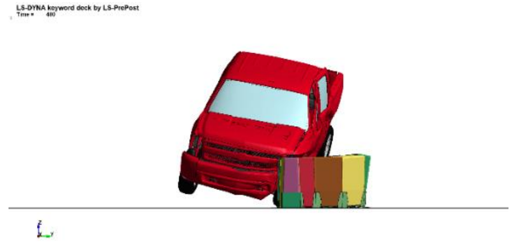
(120 ms)



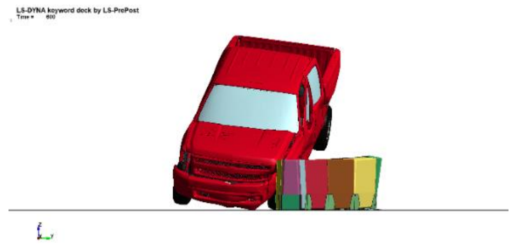
(240 ms)



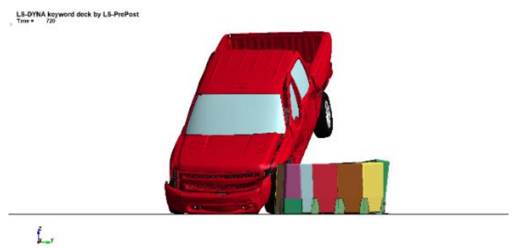
(360 ms)



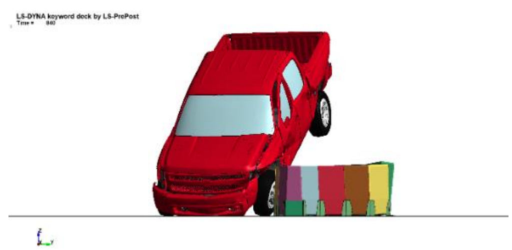
(480 ms)



(600 ms)



(720 ms)



(840 ms)

Figure 45. Sequential Images of Concept No. 17 Simulation

4.3.5 Concept No. 18 Results

Concept no. 18 was the only concept selected to evaluate the performance of the barrier that used steel as the main structural component. The advantages of this design were that it was much lighter than the traditional F-shape PCB, used strong connections at the joints that could effectively transfer moment, and the steel face was expected to decrease damage upon impact as compared to a PCB with a concrete face. This PCB concept measured 12.25 in. wide by 32 in. tall and weighed roughly 250 lb/ft. The full details of the barrier are tabulated in Table 12.

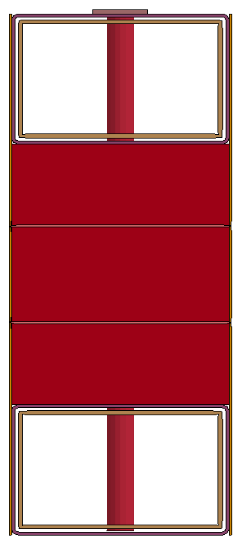


Figure 46. Cross Section of Concept No. 18

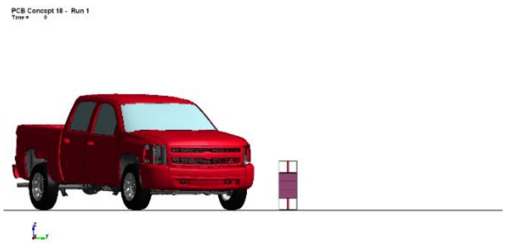
Table 12. Concept No. 18 Barrier Data

Barrier Data	
Height (in.)	32
Width (in.)	12.25
Segment Length (ft)	12.5
Total Segment Weight (lb)	3,139
Linear Weight (lb/ft)	251
Connection Type	Nested HSS & Pins

Concept no. 18 exhibited acceptable MASH safety performance, but the maximum lateral barrier displacement was 67.1 in., far exceeding the design goal of 36 in. The simulation results are provided in Table 13, and sequential images of the simulation are shown in Figure 47. Due to the exceedingly large barrier deflection and the expected cost of the steel used in the barrier, concept no. 18 was not recommended as a viable design.

Table 13. Concept No. 18 Simulation Results

Evaluation Criteria		Simulation Results
Max. Vehicle Roll (deg.)		11.6
Max. Vehicle Pitch (deg.)		3.6
Max. Bumper Climb (in.)		1.5
OIV (ft/s)	**Longitudinal**	12.8
	Lateral	18.1
ORA (g's)	**Longitudinal**	3.0
	Lateral	14.5
Barrier Knee Angle (deg.)		7.3
Maximum Lateral Dynamic Barrier Deflection (in.)		67.1



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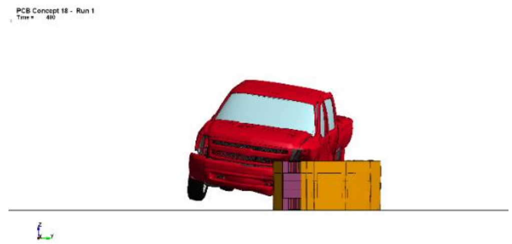

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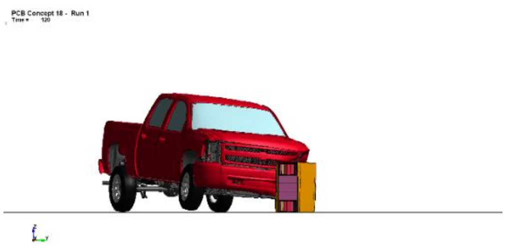

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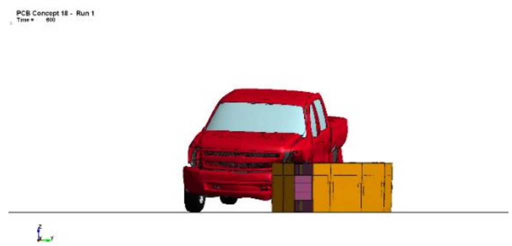

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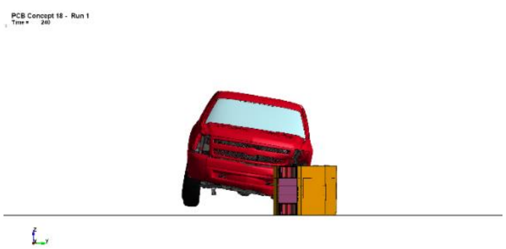

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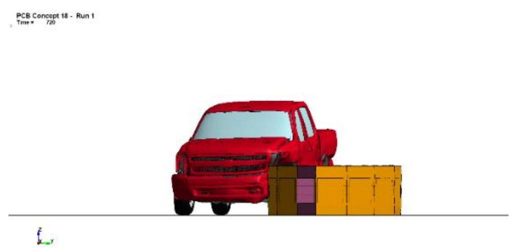

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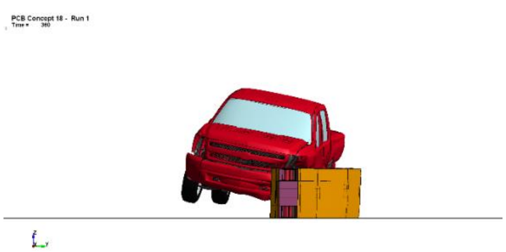

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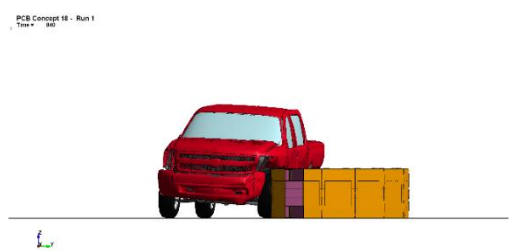


(840 ms)

Figure 47. Sequential Images of Concept No. 18 Simulation

4.3.6 Concept No. 19 Results

Concept no. 19 was meant to simplify the installation and inspection process by consisting of only concrete barrier segments and no connection hardware. The barrier segments were connected by simply staggering the placement of the top and bottom segments. The first version of the concept, concept no. 19A, measured 24 in. wide by 32 in. tall and weighed 716 lb/ft. The barrier cross section is shown in Figure 48, and measurements are listed in Table 14.

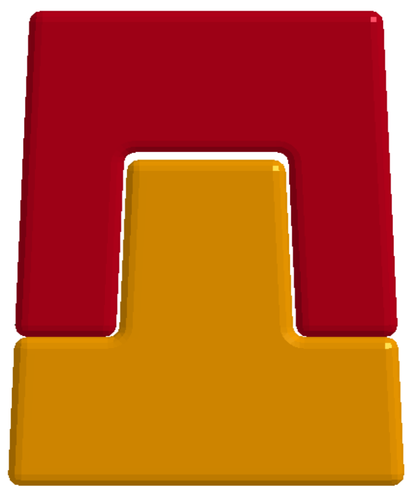


Figure 48. Cross Section of Concept No. 19A

Table 14. Concept No. 19A Barrier Data

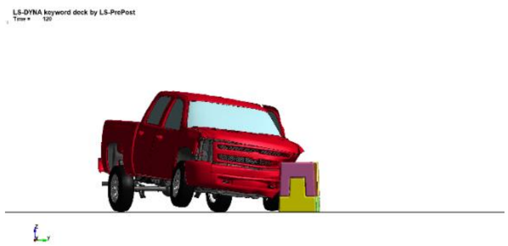
Barrier Data	
Height (in.)	32
Width (in.)	24
Segment Length (ft)	12.5
Total Segment Weight (lb)	8,950
Linear Weight (lb/ft)	716
Connection Type	Staggered & Interlocking Segments

The advantages of this barrier concept included the low cost due to the elimination of connection hardware and the expected ease at which drainage, lifting points, and anchorage could be implemented. The disadvantages were that the barrier would require two casting shapes and unique end sections to fill the half-segment gap due to the staggered segments, and a large width would be needed to fit reinforcement, resulting in a heavy barrier. Concept 19A resulted in acceptable safety criteria and a maximum barrier displacement of 8.4 in. The simulation results are provided in Table 15, and the sequential images of the simulation are shown in Figure 49.

Table 15. Concept No. 19A Simulation Results

Evaluation Criteria		**Simulation Results**
Max. Vehicle Roll (deg.)		21.8
Max. Vehicle Pitch (deg.)		7.6
Max. Bumper Climb (in.)		2.1
OIV (ft/s)	**Longitudinal**	15.1
	Lateral	22.3
ORA (g's)	**Longitudinal**	5.2
	Lateral	16.7
Barrier Knee Angle (deg.)		0.6
Maximum Lateral Dynamic Barrier Deflection (in.)		8.4

(0 ms)



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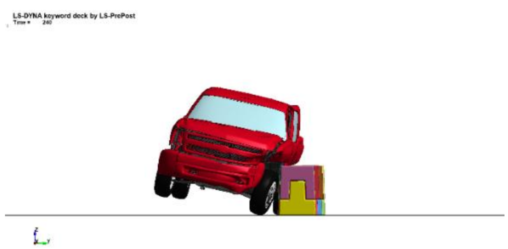

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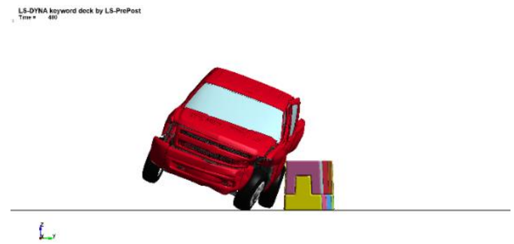

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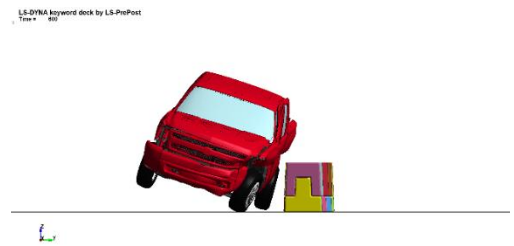

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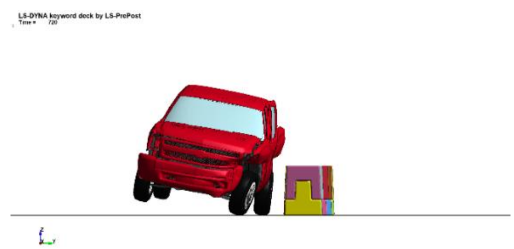

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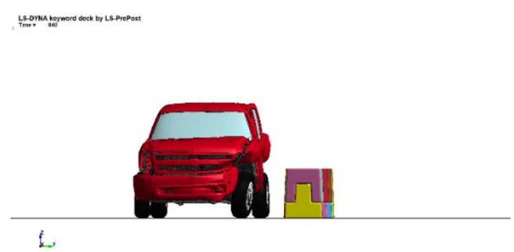


(840 ms)

Figure 49. Sequential Images of Concept No. 19A Simulation

After internal discussions with members of the MwRSF research team, five additional versions of concept no. 19 were modeled to further investigate how modifications of the original concept no. 19A design could take advantage of the very low PCB displacement while improving other characteristics such as the weight and slope of the barrier face. Concept no. 19B featured an inverted slope to further decrease bumper climb and vehicle roll. Concept no. 19C featured a revised stub shape to allow for easier reinforcement design. The stub shape was revised from the original stub shape of roughly 10 in. wide at the stub base by 12 in. tall with a 1:12 taper to a new shape of roughly 9 in. wide at the base by 12 in. tall with a 1:6 taper. It also used a larger gap for construction tolerance around the interlocking stub of ½ in. compared to ¼ in. with concept nos. 19A and 19B. Concept no. 19D featured a reduced-width cross-section of only 18 in. wide compared to the original 24 in. in order to reduce barrier weight and footprint. The gap size in concept no. 19D was reduced to ⅜ in. in order to balance construction tolerance and the expected barrier deflection due to extra movement resulting from a larger gap. The stub dimensions were decreased to 6 in. wide at the base by 12 in. tall with a 1:12 taper to fit within the smaller cross section. Concept no. 19E consisted of the same cross-section as concept no. 19D with 8-ft long segments instead of 12.5-ft long segments. Concept 19F used the same 18-in. wide and 8-ft long segments as concept no. 19E, but featured a shortened stub to reduce the reinforcement needed in the connecting stubs of the barrier. The stub height was shortened from 12 in. tall to 6 in. tall but kept the same 6-in. width and taper. The different versions of concept no. 19 are shown in Figure 50, and design details are provided in Table 16.

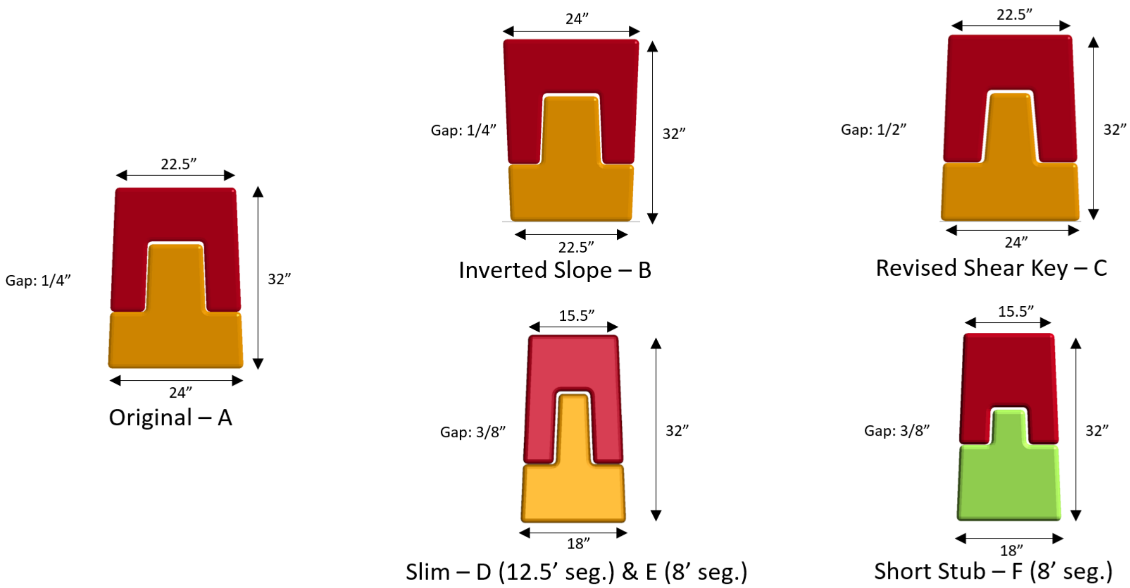


Figure 50. Variations of Concept No. 19

Table 16. Concept No. 19 Variations Barrier Data Comparison

Barrier Data						
Concept No.	19A	19B	19C	19D	19E	19F
Height (in.)	32	32	32	32	32	32
Width (in.)	24	24	24	18	18	18
Segment Length (ft)	12.5	12.5	12.5	12.5	8	8
Top Segment Weight (lb)	4,452	4,729	4,746	3,516	2,250	2,166
Bottom Segment Weight (lb)	4,498	4,222	4,143	3,018	1,943	2,101
Linear Weight (lb/ft)	716	716	711	523	524	533

The results of each of these concepts are listed in Table 17. Overall, concept nos. 19A, 19B, and 19C experienced smaller deflections due to the large barrier weights, however, concept no. 19C experienced more deflection than concept nos. 19A and 19B due to the larger gap in between the interlocking stubs. Concept nos. 19D and 19E were lighter than the first three variations, and experienced higher displacements due to the decreased weight. However, the displacements were still well below the design goal of 36 in. Excessive tipping behavior was observed in the simulation for concept no. 19F, and it was determined that the shortened stub allowed barrier segments to rotate and lift adjacent segments. The larger stub heights in the previous concept no. 19 variations did not experience this behavior since the stub was tall enough to restrain the tipping motion and improve continuity between adjacent segments. A comparison of the tipping behavior between concept nos. 19E and 19F is shown in Figure 51.

Table 17. Comparison of Concept No. 19 Variations Simulation Results

Concept No.		**19A**	**19B**	**19C**	**19D**	**19E**	**19F**
Max. Vehicle Roll (deg.)		21.8	19.9	19.8	19.3	16.1	16.4
Max. Vehicle Pitch (deg.)		7.6	6.5	7.5	7.2	6.4	8.6
Max. Bumper Climb (in.)		2.1	1.2	3.5	2.0	2.4	2.5
OIV (ft/s)	**Longitudinal**	15.1	16.6	15.8	14.8	14.3	14.5
	Lateral	22.3	20.8	21.8	21.5	20.2	20.1
ORA (g's)	**Longitudinal**	5.2	4.0	5.2	4.1	5.3	5.4
	Lateral	16.7	16.0	15.7	16.0	16.2	15.1
Barrier Knee Angle (deg.)		0.6	0.6	1.5	1.0	1.6	1.7
Maximum Lateral Dynamic Barrier Deflection (in.)		8.4	8.8	13.2	15.0	24.0	29.0

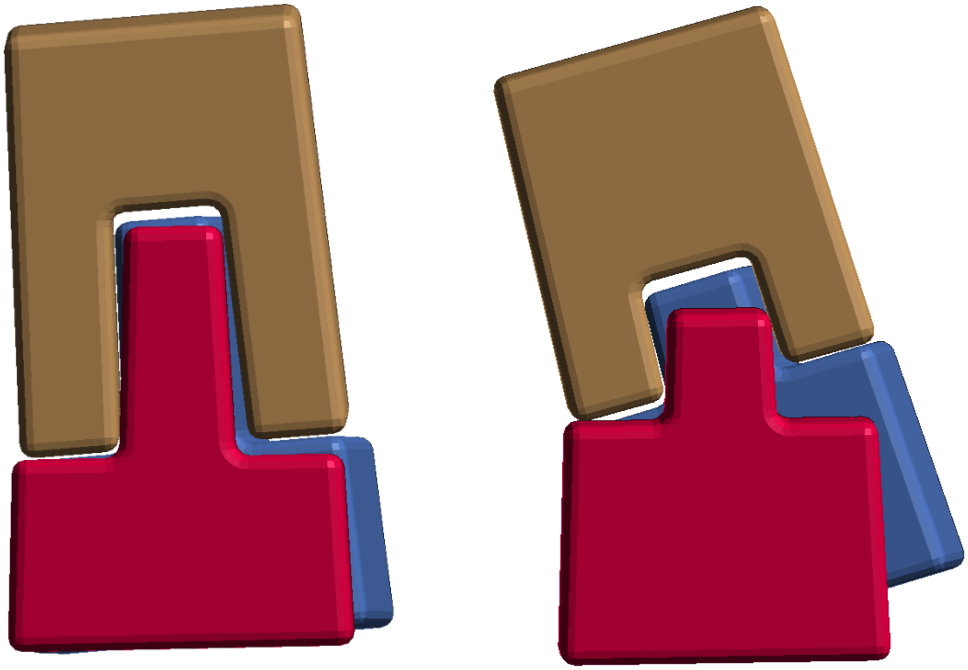


Figure 51. Comparison of Tipping Behavior in Concept Nos. 19E (Left) and 19F (Right)

To avoid this tipping behavior, modification to the size and shape of the interlocking stub would be needed and could be conducted in future phases of the research. However, the general design of concept no. 19 was acceptable and resulted in displacements that were much less than the design goal of 36 in. Specifically, concept nos. 19A, 19C, 19D, and 19E were recommended as viable designs due to the low simulated displacements.

4.3.7 Concept No. 16 Results

After analyzing the first five design concepts, a sixth concept was investigated. Concept no. 16 was selected as the sixth design due to its resemblance to concept no. 19 and the ability to use identical barrier segments on the top and the bottom. The first version of concept no. 16 measured 18 in. wide by 32 in. tall and weight approximately 580 lb/ft. The barrier cross section is shown in Figure 52, and barrier details are listed in

Table 18. The results for the first variation of the concept, concept no. 16A, are provided in Table 19, with sequential images of the simulation shown in Figure 53.

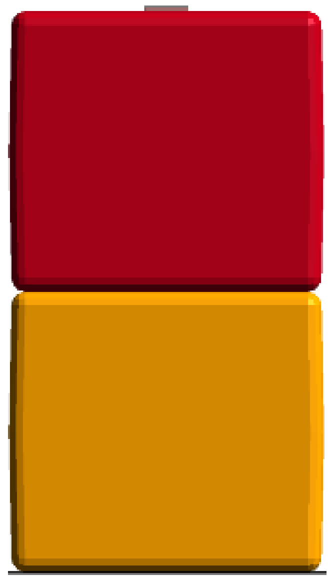


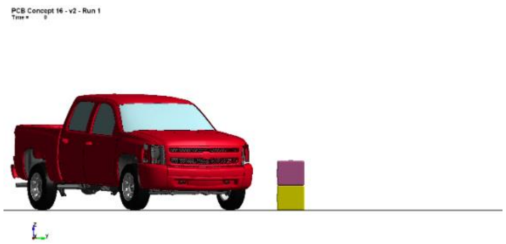
Figure 52. Cross Section of Concept No. 16A

Table 18. Concept No. 16A Barrier Data

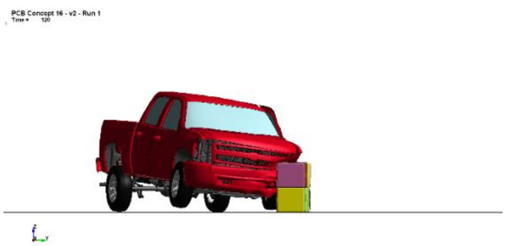
Barrier Data	
Height (in.)	32
Width (in.)	18
Segment Length (ft)	12.5
Total Segment Weight (lb)	7,200
Linear Weight (lb/ft)	580
Connection Type	Staggered & Pinned Segments

Table 19. Concept No. 16A Simulation Results

Evaluation Criteria		Simulation Results
Max. Vehicle Roll (deg.)		18.5
Max. Vehicle Pitch (deg.)		6.6
Max. Bumper Climb (in.)		2.1
OIV (ft/s)	**Longitudinal**	15.8
	Lateral	20.1
ORA (g's)	**Longitudinal**	4.4
	Lateral	15.3
Barrier Knee Angle (deg.)		1.0
Maximum Lateral Dynamic Barrier Deflection (in.)		13.3



(0 ms)

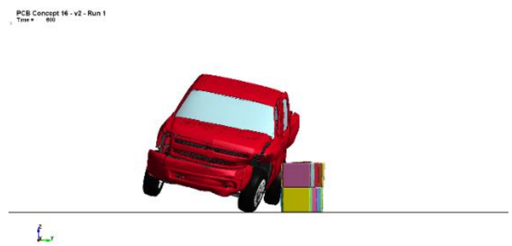


(120 ms)

(240 ms)

(360 ms)

(480 ms)



(600 ms)

(720 ms)

(840 ms)

Figure 53. Sequential Images of Concept No. 16A Simulation

Due to the barrier tipping observed in the simulation of concept no. 16A, shown in the sequential images above, two variations of concept no. 16 were simulated to reduce or eliminate the tipping behavior. Concept no. 16B featured a width reduced to 16 in. and larger, 1.75-in. diameter drop pins. These changes were made to reduce the barrier weight and decrease the bending in the drop pins, which was allowing separation between the top and bottom barrier segments. Concept no. 16C featured an 18-in. width and the larger, 1.75-in. diameter drop pins. The width was increased back to 18 in. after tipping was still observed in the simulation for concept no. 16B. There was still some tipping behavior observed in the simulation for concept no. 16C, but it was reduced compared to concept nos. 16A and 16B and considered acceptable. Cross sections for the barrier variations are shown in Figure 54. The measurements for the three variations of concept no. 16 are listed in Table 20, and the simulation results are compared in Table 21.

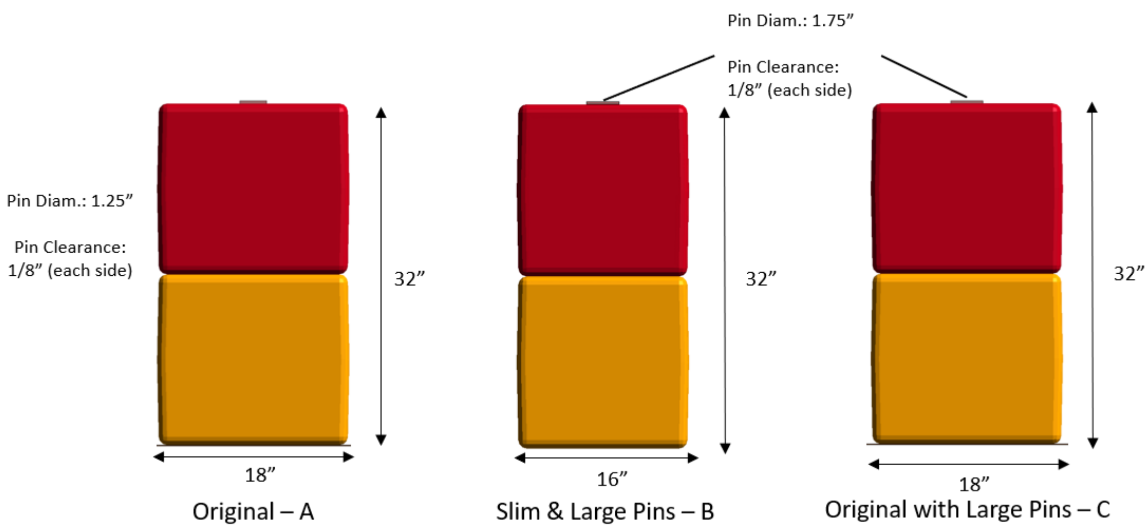


Figure 54. Cross Sections of Concept No. 16 Variations

Table 20. Comparison of Concept No. 16 Variations Barrier Data

Barrier Data			
Concept No.	16A	16B	16C
Height (in.)	32	32	32
Width (in.)	18	16	18
Segment Length (ft)	12.5	12.5	12.5
Total Segment Weight (lb)	7,200	6,400	7,200
Linear Weight (lb/ft)	580	513	580

Table 21. Comparison of Concept No. 16 Variations Simulation Results

Evaluation Criteria		**Simulation Results**		
Concept No.		16A	16B	16C
Max. Vehicle Roll (deg.)		18.5	18.4	19.1
Max. Vehicle Pitch (deg.)		6.6	6.4	6.8
Max. Bumper Climb (in.)		2.1	1.9	1.6
OIV (ft/s)	**Longitudinal**	15.8	16.4	16.2
	Lateral	20.1	20.2	20.0
ORA (g's)	**Longitudinal**	4.4	4.17	3.96
	Lateral	15.3	15.0	15.5
Barrier Knee Angle (deg.)		1.0	0.9	0.9
Maximum Lateral Dynamic Barrier Deflection (in.)		13.3	15.6	12.4

Based on the results observed during the simulations for concept no. 16, all the variations met the displacement goals and did not exceed any MASH safety criteria.

Since concept no. 16C resulted in the best performance and minimized the tipping behavior, this variation was recommended as a viable design.

4.4 Summary of Viable Concepts

Each PCB concept was judged based on vehicle safety and barrier performance. PCB concepts that met or exceeded the design criteria and passed MASH test designation no. 3-11 safety criteria were recommended as viable designs. Those that did not meet the criteria were not recommended. For concept nos. 1, 16, and 19, variations of the original concept design were simulated in order to further investigate the performance improvements based on slight modifications. These variations offered additional data that showed why certain concepts were more viable designs and how their performance could be improved through future development efforts.

Concept nos. 2, 17, and 18 were not recommended as viable PCB designs. Concept no. 2 exhibited barrier displacement of 62.9 in., which exceeded the design goal of 36 in. Modifications necessary for improving the performance would result in a design similar to concept no. 1, so no further investigation was done with this design. Concept no. 17 showed high potential for vehicle snag due to discontinuity between the tops of adjacent barrier segments, and simulations resulted in barrier displacement that exceeded the design criteria. Thus concept no. 17 was not recommended, and it would need additional modification to address these issues. Concept no. 18 was not recommended due to excessive barrier displacement and expected high manufacturing cost from the amount of steel used in the barrier

Concept nos. 1, 16, and 19 were recommended as viable PCB designs while some of their respective variations were not recommended. Concept no. 1A and Concept no.

1B both showed acceptable safety performance, however concept no. 1A had slightly lower barrier displacement than concept no. 1B. Since the difference between the two variations was only the pin arrangement, the general design of concept no. 1 was recommended as a viable design. Concept nos. 16A and 16B showed issues with barrier segments tipping upon impact, while concept no. 16C improved this behavior. Thus, concept no. 16C was recommended as a viable design, and concept nos. 16A and 16B were not recommended. All six variations of concept no. 19 demonstrated acceptable safety and barrier performance, however, concept no. 19B did not show improvement over concept no. 19A, and concept no. 19F showed issues with tipping. Thus, these two variations were not recommended, while concept nos. 19A, 19C, 19D, and 19E were recommended as viable designs. The concepts that were recommended are shown in Figure 55, while the concepts that were not recommended are shown in Figure 56.

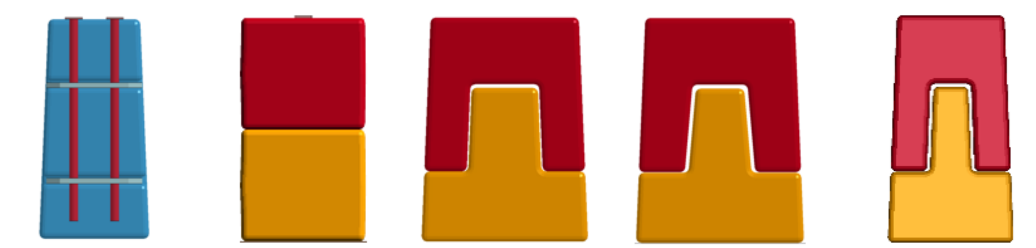


Figure 55. Recommended Concept Designs
(*8-ft segment lengths)

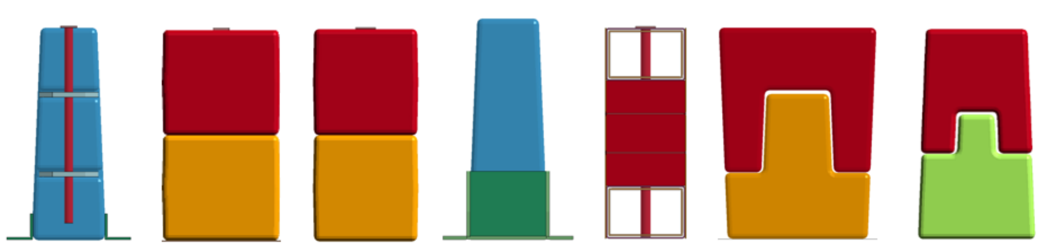


Figure 56. Not Recommended Concept Designs
(*8-ft segment lengths)

Chapter 5 Selection of Preferred Design

5.1 Comparison of Simulation Results

Once all simulations were completed and the results were individually analyzed, bar plots were created to easily compare each of the design concepts and their variations. These plots were analyzed by MwRSF team members and later presented during a meeting to Pooled Fund Program member states to illustrate the differences between the design concepts. Figure 57 shows a comparison of the cross-sections of all the design concepts.

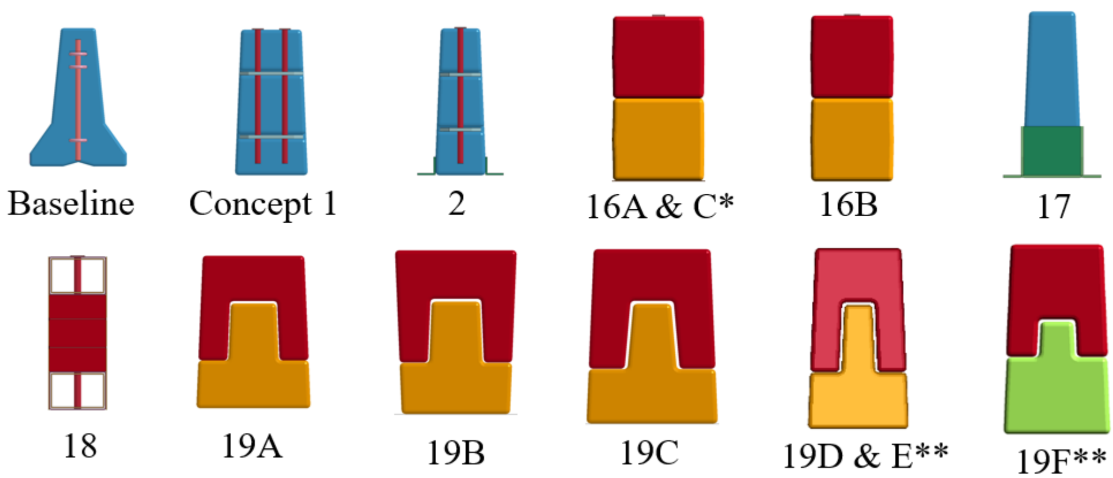


Figure 57. Visual Comparison of Design Concept Cross-Sections
(*Uses larger pins, **8-ft segment lengths)

The first measurement for comparison between the barriers was the maximum amount of dynamic deflection that occurred during the impact. This displacement was only measured laterally, as any longitudinal displacement was insignificant. The maximum lateral barrier displacement is shown in Figure 58. In the following bar plots, the orange dashed line represents the results from the baseline simulation and is extended across the plot for easy comparison to the PCB concept results.

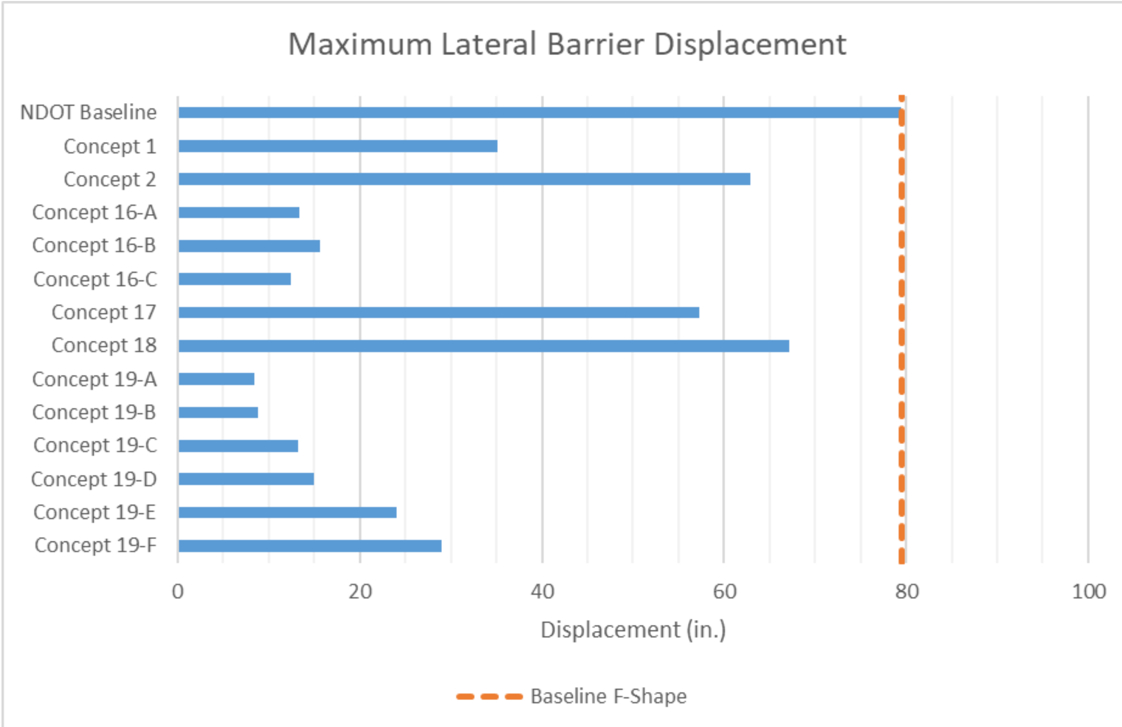


Figure 58. Comparison of Maximum Lateral Barrier Displacement Observed in Simulations

The baseline F-shape barrier resulted in nearly 80 in. of barrier displacement, while all the concept designs showed reduced displacement. However, concept nos. 2, 17, and 18 did not meet the design criteria limit of 36 in. Concept nos. 1, 16, and 19 resulted in displacements ranging from 8 in. to 35 in., all below the design criteria. Thus, concept nos. 1, 16, and 19 were further investigated with slight modifications to the designs discussed in previous sections, which still resulted in displacements below the design criteria.

MASH has specific safety criteria for test designation no. 3-11 impacts, which include vehicle roll, vehicle pitch, lateral and longitudinal Occupant Impact Velocity (OIV), and lateral and longitudinal Occupant Ridedown Acceleration (ORA). MASH sets maximum limits for both vehicle roll and pitch to 75 degrees. Lateral and longitudinal

OIV have a preferred limit of 30 ft/s and a maximum limit of 40 ft/s. Lateral and longitudinal ORA have a preferred limit of 15 g's and a maximum limit of 20.49 g's [1]. The simulation results for these criteria are shown in Figures 59 through 64. In the following bar plots, the grey line represents the maximum limit in MASH for the given measure. If that maximum limit was within the range of the simulation results, it is present in the graph, and if the limit was not within range, it was not shown.

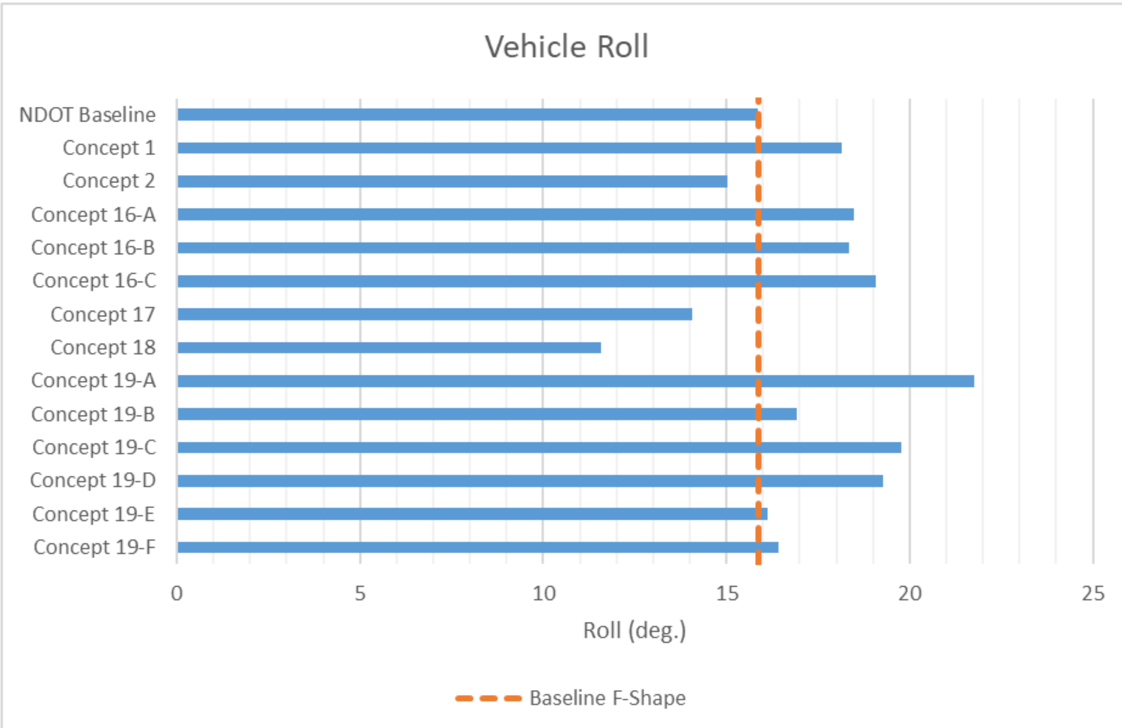


Figure 59. Comparison of Vehicle Roll Observed in Simulations

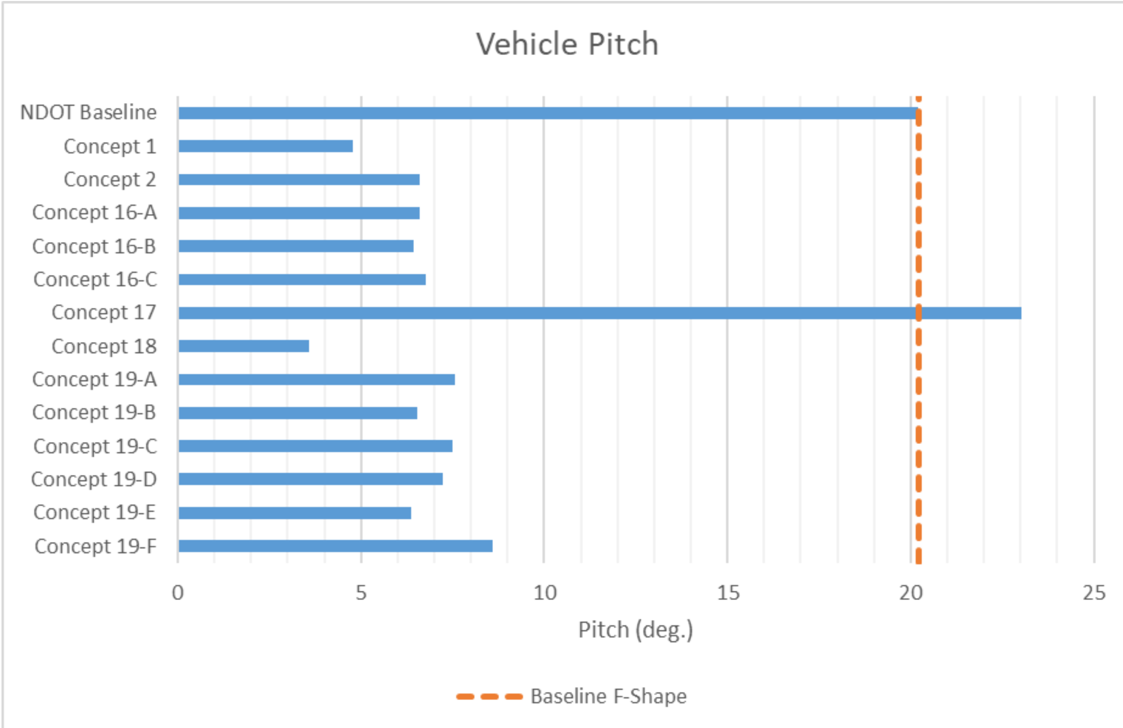


Figure 60. Comparison of Vehicle Pitch Observed in Simulations

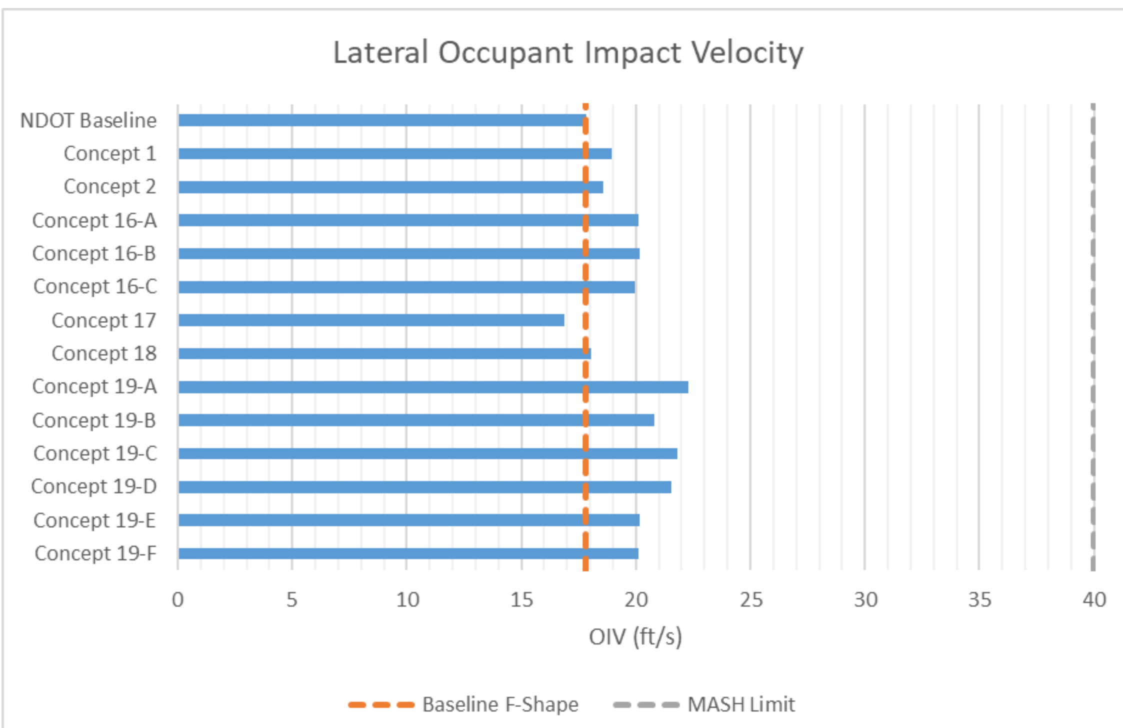


Figure 61. Comparison of Lateral OIV Observed in Simulations

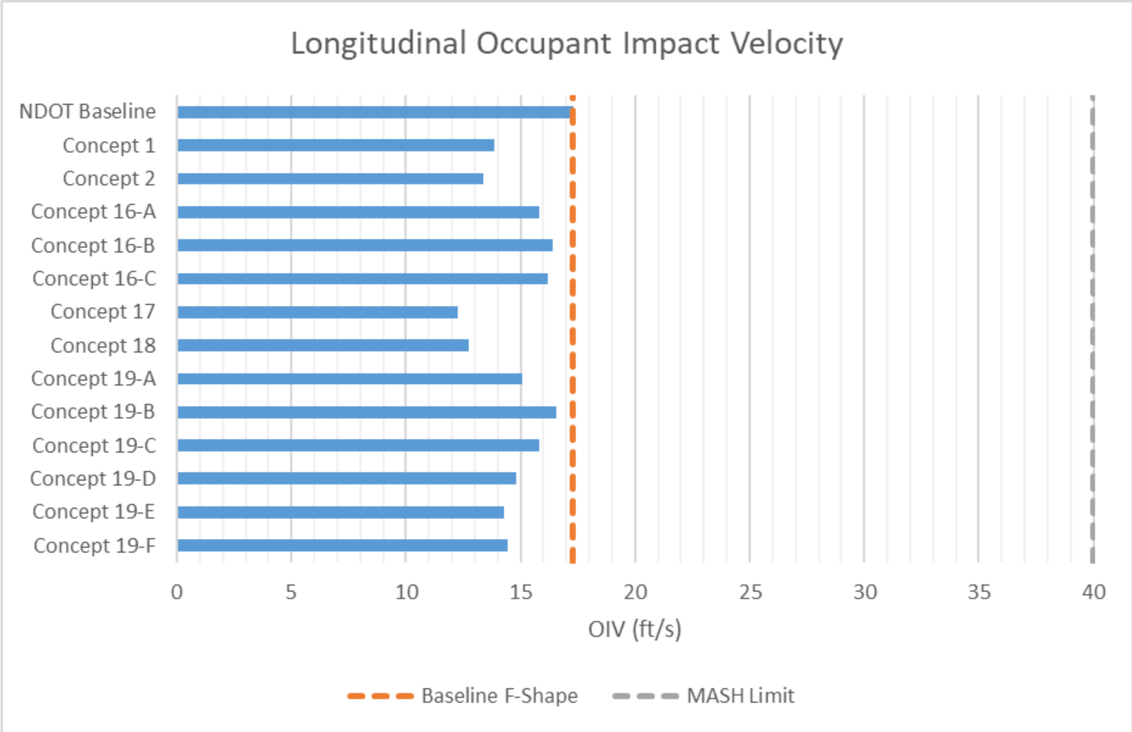


Figure 62. Comparison of Longitudinal OIV Observed in Simulations

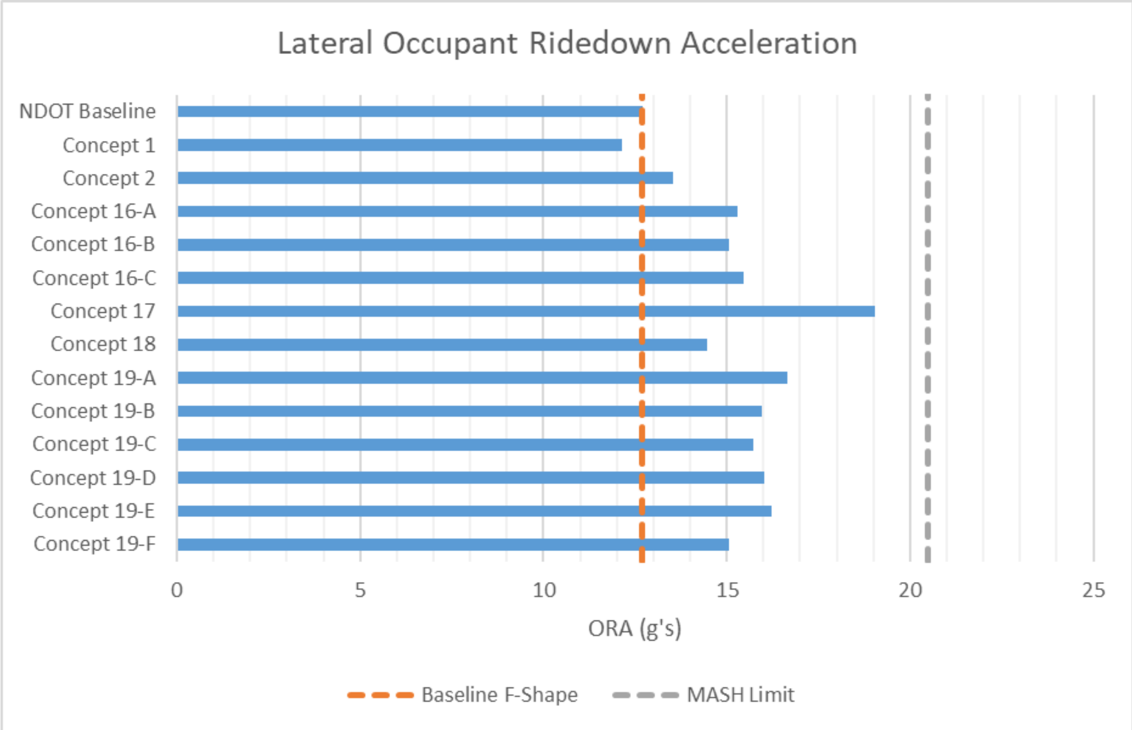


Figure 63. Comparison of Lateral ORA Observed in Simulations

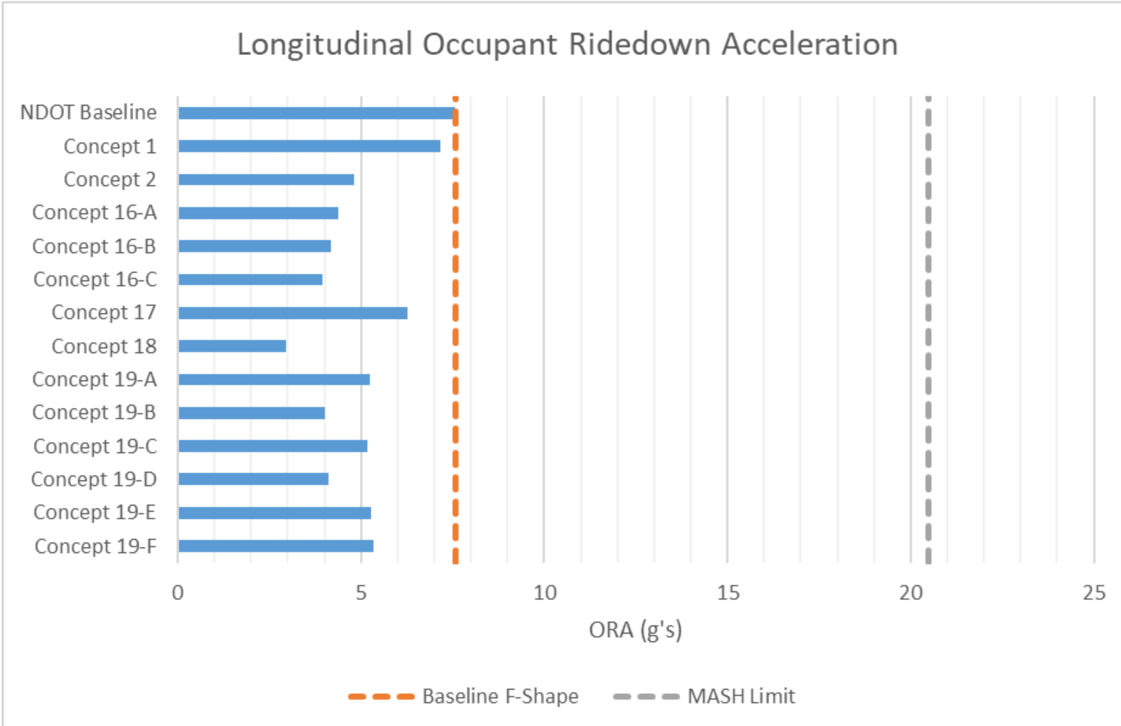


Figure 64. Comparison of Longitudinal ORA Observed in Simulations

As shown in Figure 59, vehicle roll tended to vary among the design concepts but was within 5 degrees of the baseline F-Shape PCB. None of the PCB systems exceeded the MASH maximum limit of 75 degrees. Three PCB concepts resulted in lower vehicle roll than the baseline, which were concept nos. 2, 17, and 18. However, these concepts were the designs that resulted in excessive barrier displacement, indicating that there is an inverse relationship between vehicle roll and barrier displacement. Since vehicle roll for all the simulations was well below the MASH maximum limit, this measure did not pose a concern. Vehicle pitch was shown to be greatly reduced in most of the design concepts compared to the baseline F-Shape, except for concept no. 17 which resulted in an increase in vehicle pitch. As discussed in the results section, concept no. 17 had issues related to vehicle snag that caused excessive vehicle instability.

For the occupant safety criteria measurements, OIV and ORA, none of the simulations resulted in values that exceeded MASH maximum limits. The resulting values for lateral OIV and ORA were mostly consistent with or slightly increased compared to the value from the baseline F-Shape simulation. Values for longitudinal OIV and ORA were slightly reduced compared to the F-Shape. It was theorized that the lower longitudinal values were due to the PCB concepts having more continuity between barrier segments compared to the pin and loop connections of the F-Shape PCB, resulting in lower knee angles between segments and creating a smoother interface for the vehicle.

The bumper climb was an additional concern regarding vehicle behavior with the F-Shape PCB. The simulation for the F-Shape PCB resulted in roughly 16 in. of the climb. This was measured by selecting the first point of contact between the vehicle bumper and the barrier and recording its vertical displacement throughout the impact event. All the PCB design concepts had greatly decreased bumper climb below 5 in., as shown in Figure 65.

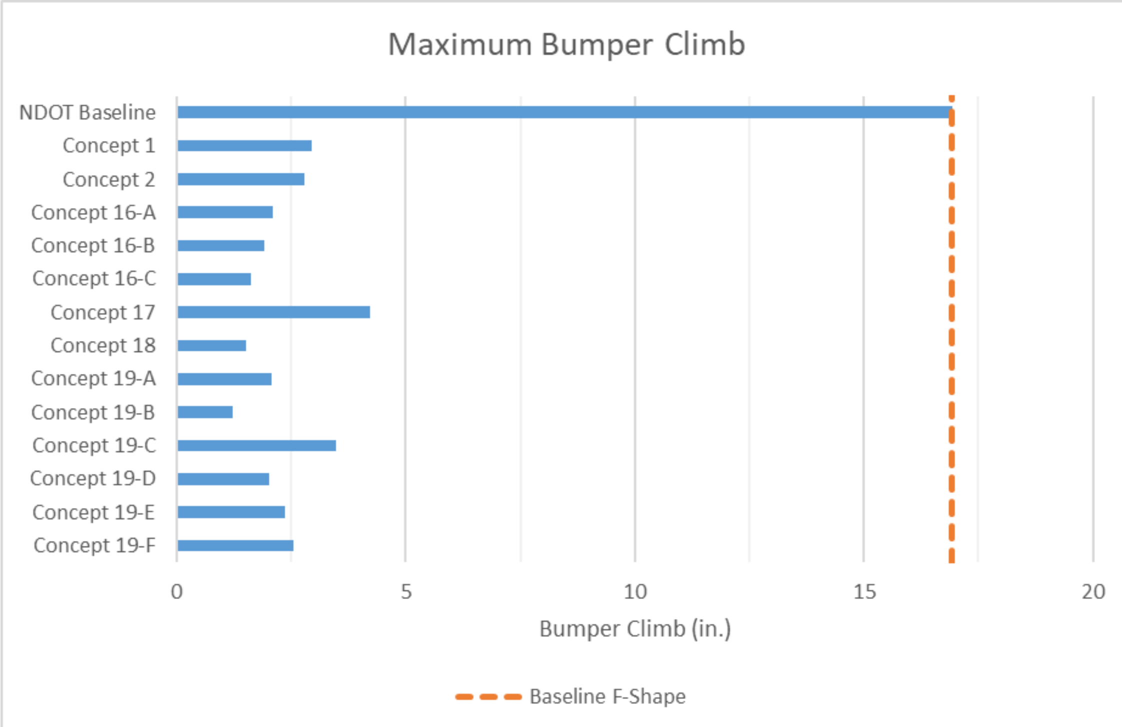


Figure 65. Comparison of Bumper Climb Observed in Simulations

Several other design criteria were identified as part of the survey distributed to Midwest Pooled Fund Program members, including PCB weight and cost. Both characteristics were estimated for each concept based on preliminary designs and did not include consideration of any finalized reinforcement design. However, while the weight or cost of any finalized design may vary from the conceptual design, the approach was considered acceptable to compare the F-Shape PCB and design concepts during the current research phase. Weight was estimated by measuring the volume of each component multiplied by an estimate of material density. The cost was estimated by multiplying the weight of materials used in the barrier by an estimate of the material cost per unit weight. The comparison for the estimated barrier cost is shown in Figure 66.

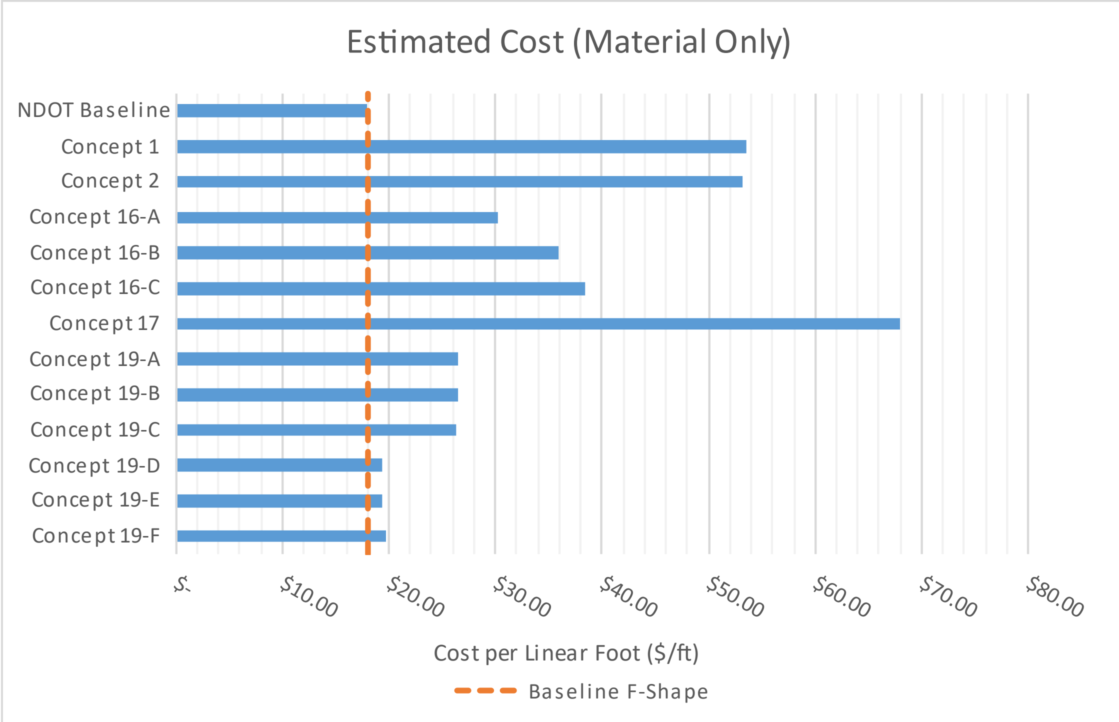


Figure 66. Comparison of Estimated Material Cost for PCB Concepts

Material costs for all PCB concepts showed an increase compared to the baseline F-Shape PCB. This is primarily due to the light weight of the F-Shape PCB and its connection hardware, which weighed approximately 5,000 lb per 12.5-ft segment. While several barriers had total weights similar to the F-Shape, the major difference was in the weight of the steel connection hardware. The connection hardware for the F-Shape PCB weighed less than 20 lb, while the connection hardware for concept no. 17, for example, weighed nearly 300 lb. It should also be noted that the cost for concept no. 18, the steel PCB concept, is not included in Figure 66, since its estimated cost of roughly $243 per foot greatly exceeded the range of the bar plot for the other concepts. Concept nos. 19-D, 19-E, and 19-F had similar costs to the F-Shape barrier, which resulted from the roughly 130 percent increase in weight compared to the F-Shape offsetting the cost decrease due to the lack of steel connection hardware in the variations of concept no. 19.

Barrier weight was a concern since the PCB system would need to be lifted during transportation and installation. The design criteria identified from the survey required that segment weight be limited to less than 7,000 lb for this reason. However, since concept nos. 16 and 19 consisted of multiple segments stacked together to form the full barrier cross section, they could be lifted separately during installation. As shown in Figure 67, only concept no. 1 had a higher segment weight than the baseline F-Shape PCB. All the other PCB concepts had lower maximum segment weights, indicating they could be lifted by equipment used to install the F-Shape PCB system.

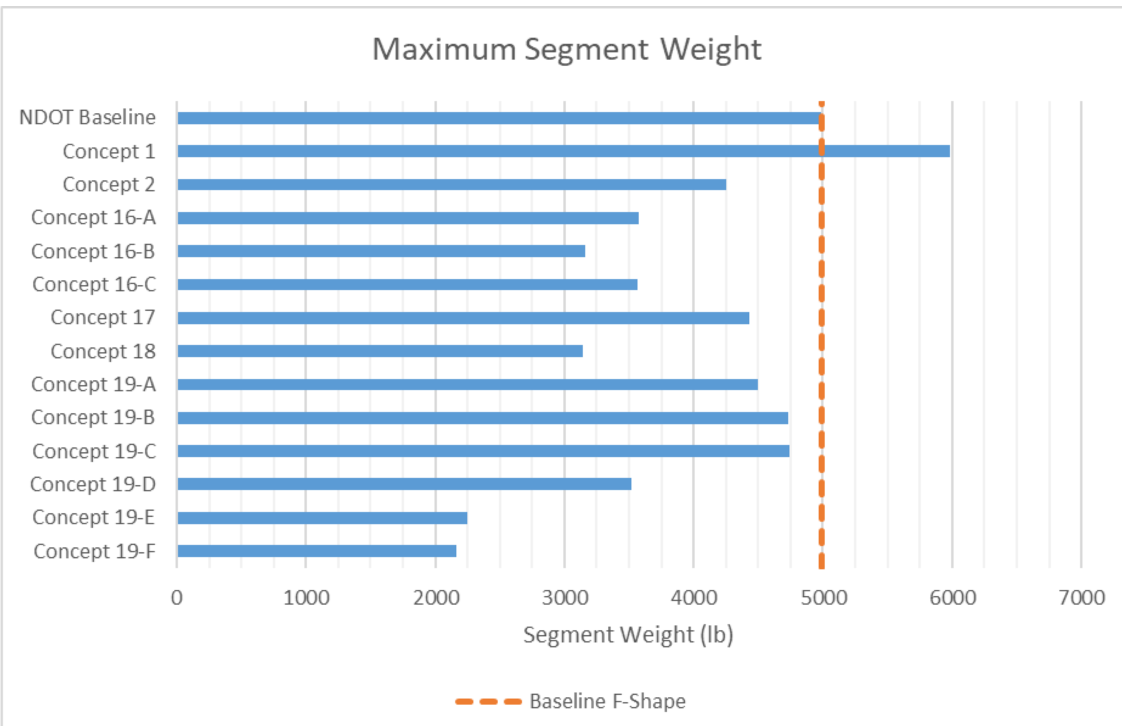


Figure 67. Comparison of Maximum Estimated Segment Weight for PCB Concepts

While this method of comparison was acceptable for considering the lifting weight limit, it was not a true comparison of the total weight of the PCB concepts. PCB systems can be installed on bridge decks, where the total weight of the PCB system is the primary concern rather than the maximum weight of individual segments. Most of the PCB concepts measured 12.5 ft in length, but concept nos. 19-E and 19-F were only 8 ft long. Therefore, to make a direct comparison, the estimated weights were normalized into linear weight. Figure 68 shows the linear weight for all the concepts compared to the baseline F-Shape PCB.

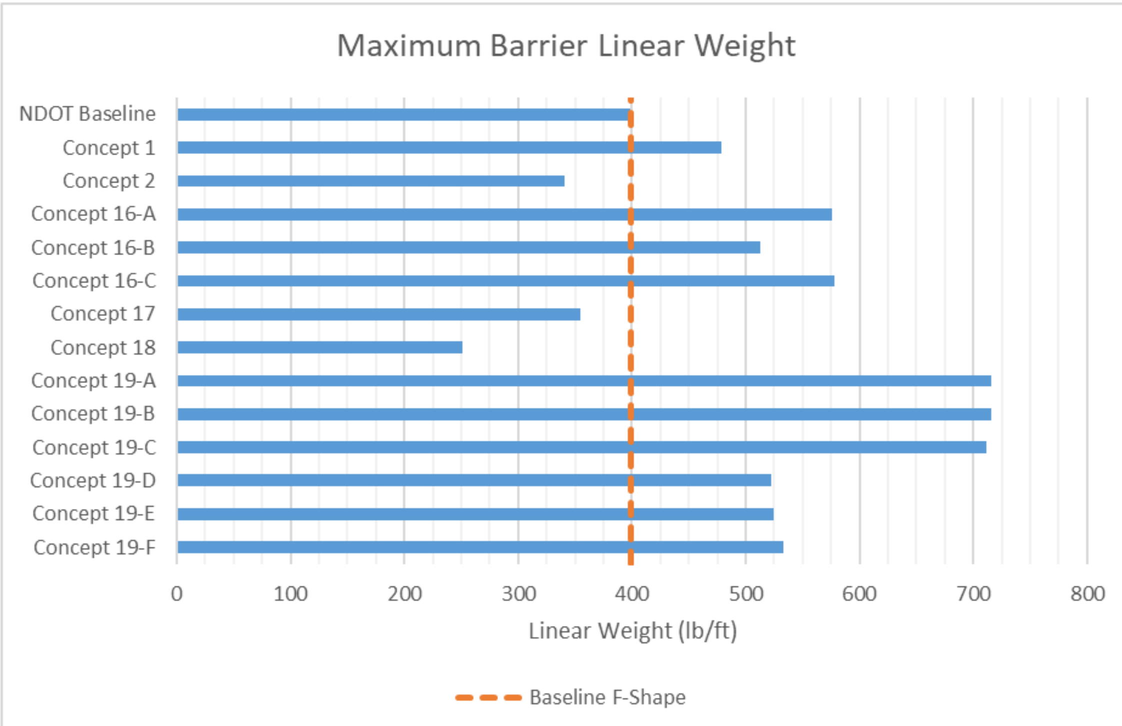


Figure 68. Comparison of Maximum Estimated Linear Barrier Weight for PCB Concepts

Most of the simulated concepts had increased linear weight compared to the baseline, with the exception of concept nos. 2, 17, and 18. It was also observed that the heaviest PCB concepts were those that resulted in the lowest maximum lateral barrier displacement. Figure 69 shows the relationship between barrier displacement and linear weight to further illustrate this relationship. A clear trend was present indicating that increased barrier weight caused a decrease in barrier displacement. This trend is due to the behavior that PCB systems utilize to redirect vehicles, primarily a combination of inertial resistance from the mass of the barrier segments and friction between the PCB segments and the pavement. Both factors are directly influenced by an increase in barrier weight. Therefore, increased barrier weight is beneficial to performance when it is within restrictions for weight based on lifting and placement on bridge decks.

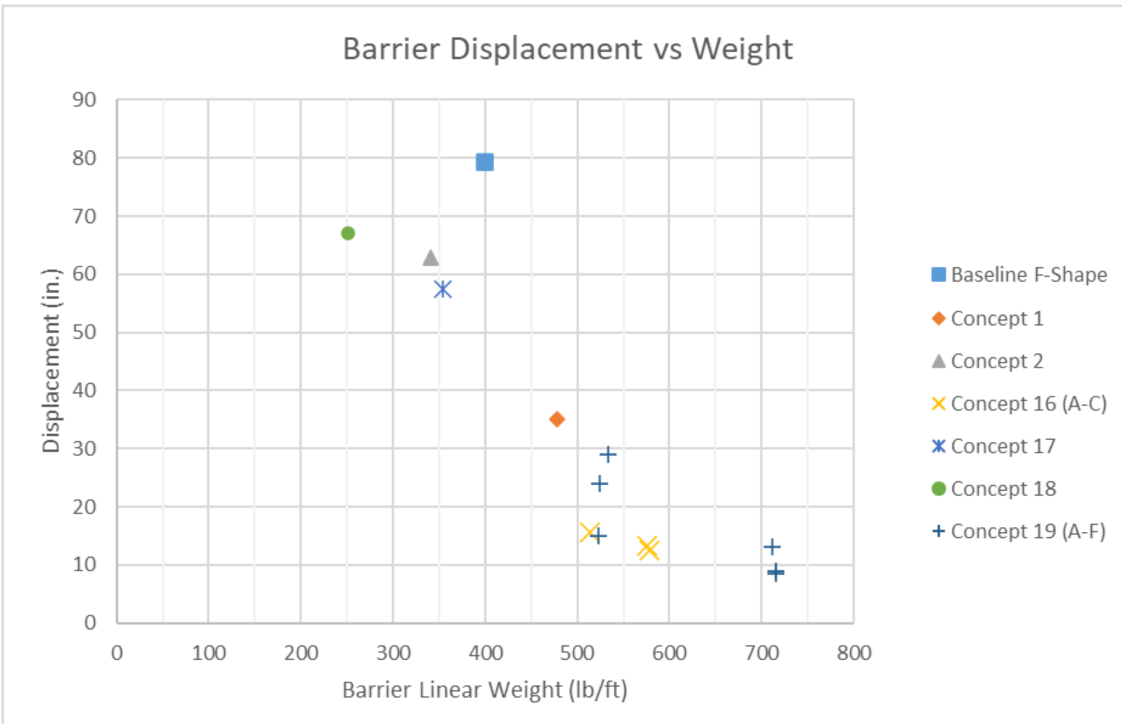


Figure 69. Simulated Lateral Barrier Displacement Versus Linear Barrier Weight

In addition to the importance of barrier weight, Figure 69 also showed that barrier displacement had some influence from the connection design used between adjacent segments. Based purely on linear weight, the baseline F-Shape PCB would be expected to have much less displacement than it exhibited in simulations and crash tests. However, the F-Shape PCB utilized pin-and-loop connections which enabled segments to rotate more than 20 degrees before locking up and more effectively transferring load to adjacent segments. The simulated PCB concepts used connection designs that limited rotation to as little as 1 degree and more effectively transferred load between segments, leading to additional reductions in displacement. Consequently, any further concept development conducted in future research phases will incorporate these observations into the final design.

5.2 Survey to Midwest Pooled Fund Program Member States

The PCB concept simulation results and comparison plots were shown to Midwest Pooled Fund Program member states to provide an update on the status of the research effort and to request feedback. After the presentation, a survey was sent to attendees to request their input on questions that did not receive clear responses in the initial design criteria survey, as well as to request them to rank the viable PCB concepts by preference. A full copy of this survey is provided in Appendix A and the results are summarized below. As was done with the previous design criteria survey, only complete survey responses were considered, and partial responses were ignored. This strategy alleviated several issues including instances where multiple responses were recorded from the same entity. The partially completed surveys showed similar distributions and responses as the completed surveys, so this method did not distort any of the overall survey results.

5.2.1 Question No. 1

The first question asked respondents to rank the three viable PCB design concepts, concept nos. 1, 16, and 19, in order of preference. Concept no. 19 was the most preferred concept, followed by concept no. 1 as the second-most preferred, and concept no. 16 as the third-most preferred concept. Figure 70 shows the distribution of the results. A higher score indicates a higher preference for that specific concept.

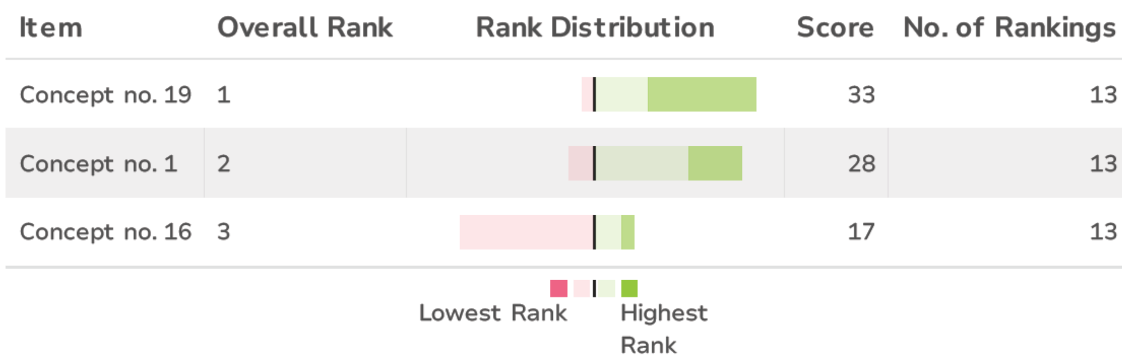


Figure 70. Survey Results for Ranking of PCB Concept Preference

5.2.2 Question No. 2

The second survey question asked respondents to indicate the methods contractors and installers use to position barrier segments. The responses to this question were needed so that appropriate lifting points could be designed in future research phases. Figure 71 shows the distribution of responses. The total percentage exceeds 100% due to respondents being able to select multiple options. Other equipment that was written in included the use of excavators, boom trucks, skid loaders, and backhoes. Thus, the finalized PCB design will need to include multiple options for lifting the barrier to accommodate the wide range of equipment.

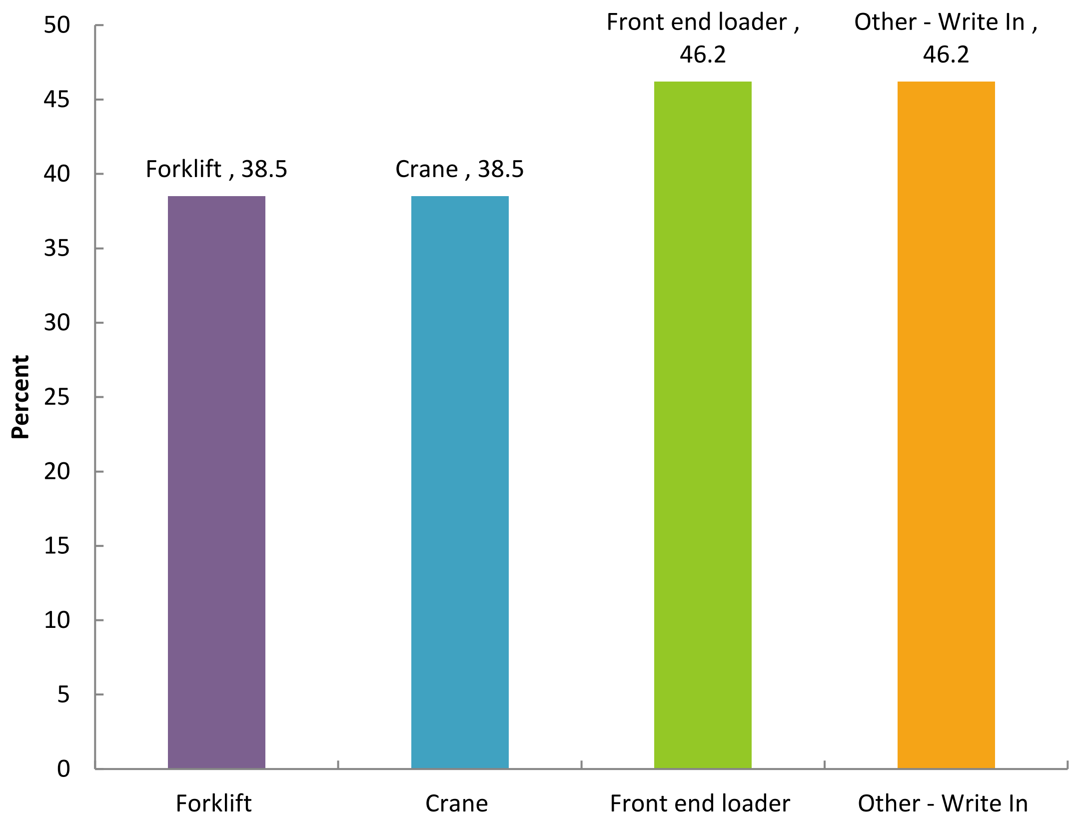


Figure 71. Survey Results for Equipment Used for Barrier Placement

5.2.3 Question No. 3

The third question asked respondents to clarify their needs regarding the minimum radius of curvature onto which the PCB system could be installed. Most responses to the previous design criteria survey ranged from 100 ft to 770 ft, but this range of responses needed to be reduced due to the importance this restraint has on the potential PCB system displacement. Since smaller curve radii require an increase in the tolerance for movement within joints, systems with smaller curve radii result in larger displacements. Figure 72 shows the range of curve radii that respondents indicated. Nearly half of the respondents requested a minimum radius of curvature between 100 and 200 ft. Thus, further development of the selected PCB concept will include efforts to reach this requirement, potentially through the optional use of shorter segment lengths that allow for installation on smaller radius curves.

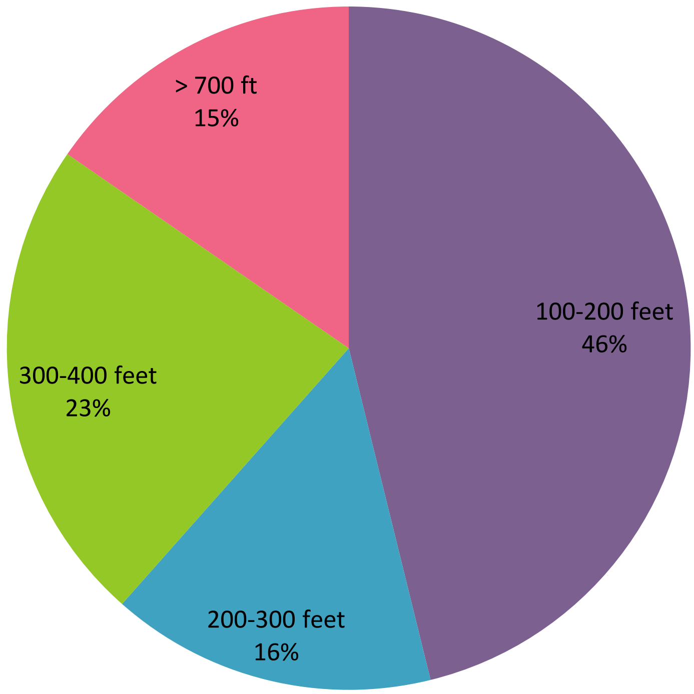


Figure 72. Survey Results for Minimum Radius of Curvature

5.2.4 Question No. 4

The fourth question requested that respondents indicate their preferred drainage needs for the new PCB concept. This was also asked in the previous design criteria survey, but responses varied and needed further clarification. Figure 73 shows the response distribution. Almost half of the responses indicated the desire for 2 to 4 ft of drainage slots per 12.5-ft. long barrier segment. Write-in responses included one slot that was 2 ft long and 2 in. high, two 1-ft. long slots per 12.5-ft. long barrier segment, and two slots 27 in. long and 3 in. high per 12.5-ft long barrier segment. Thus, a final design with 4 ft of drainage slots was expected to accommodate all users.

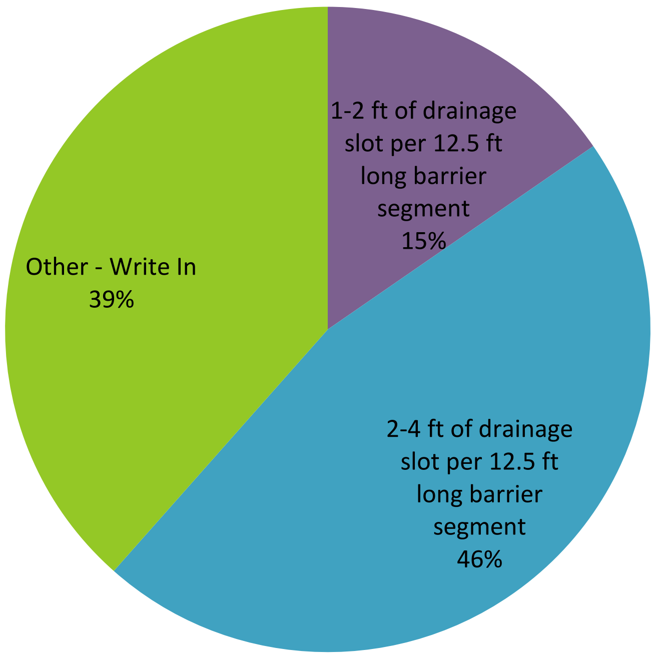


Figure 73. Survey Results for Drainage Requirements

5.2.5 Question No. 5

The fifth question asked respondents if they anticipated issues with increased barrier weight when the PCB system would be installed on a bridge deck. To provide background information to the respondents, a short study was done to investigate the effect of PCB placement on the edge of a bridge deck. This investigation found that PCB placement on overhangs near the edge of a bridge deck falls under Design Case No. 3 in AASHTO LRFD Bridge Design Specifications [14]. Design Case No. 3 consists of an analysis considering the dead loads of the PCB system, bridge deck, and wearing surface, as well as a wheel live load. Typically, this wheel load is distributed as a 1 kip/ft line load

1 ft from the face of a structurally continuous barrier. However, PCBs cannot be considered structurally continuous and so the wheel load cannot be distributed. Instead, the wheel load is represented as a 16 kip point load resisted by a limited length of the deck.

This analysis was tested with the baseline F-Shape PCB assumed to be anchored 6 in. from the edge of the bridge deck. This scenario was selected based on the current state of the practice regarding PCB placement on bridge decks and was similar to the layout tested in test no. WITD-1 conducted during a previous MwRSF study [15]. A standard deck design consisting of an 8 in. thick slab with a 5 ft overhang with a top mat of #6 rebar at 8-in. spacing and no bottom reinforcement was used in the analysis and expected to be conservative. This analysis found that the deck had a moment capacity of 13.8 kip*ft/ft, but had a moment demand of 15.9 kip*ft/ft. Since this analysis showed that the anchored F-Shape scenario was 15 percent over capacity, five other cases were tested through a parametric study to compare with other PCB concepts.

For the parametric study, the F-Shape PCB was assumed to be anchored, since it would need to be anchored in order to prevent it from displacing off the bridge deck when impacted, and this is a common installation practice. However, concept nos. 19A and 19D were not considered to be anchored, since their low lateral displacements allowed them to be installed free-standing near the edge of the deck as long as enough space was provided to accommodate the displacement. Deck overhangs of 4 ft and 5 ft were investigated, while the rest of the deck parameters remained identical to the deck described above. The results of this parametric study are shown in Table 22.

Table 22. Parametric Study for Bridge Deck Weight Limit

Deck Overhang (ft)	PCB Concept	PCB Width (in.)	PCB Weight (kip/ft)	Distance from Edge (in.)	Moment Demand (kip*ft/ft)	Percent of Capacity
4	19A	24	0.716	12	3.2	23.2%
	19D	18	0.520	14	2.6	18.5%
	Anchored F-Shape	22.5	0.399	6	8.1	58.9%
5	19A	24	0.716	12	13.0	94.2%
	19D	18	0.520	14	12.1	87.7%
	Anchored F-Shape	22.5	0.399	6	15.9	114.6%

As shown from the parametric study, the only case in which the deck capacity is exceeded is the case with the anchored F-Shape PCB installed on a 5-ft overhang. Cases with the free-standing variations of concept no. 19 were not concerning. Based on these results, it was observed that the larger PCB width and larger distance from the edge of the deck moved the wheel load close enough to the first support to alleviate its effect on the moment demand. Thus, barrier weight was not a significant factor in moment demand. Rather, the wheel load was the primary factor, and moving this load farther away from the edge of the deck caused the moment demands to drop significantly.

Based on this analysis, respondents were asked to verify with their bridge departments if they anticipated increased barrier weight to be a concern when installed on bridge decks. The distribution of responses is shown in Figure 74. The responses were almost evenly split, with slightly more respondents indicating that they did anticipate an issue with the increased barrier weight on bridge decks. Space was provided for additional comments regarding this question, and it was noted that concerns are specifically related to installation on older bridge decks. As such, these concerns will need to be taken into consideration during future phases of the design process.

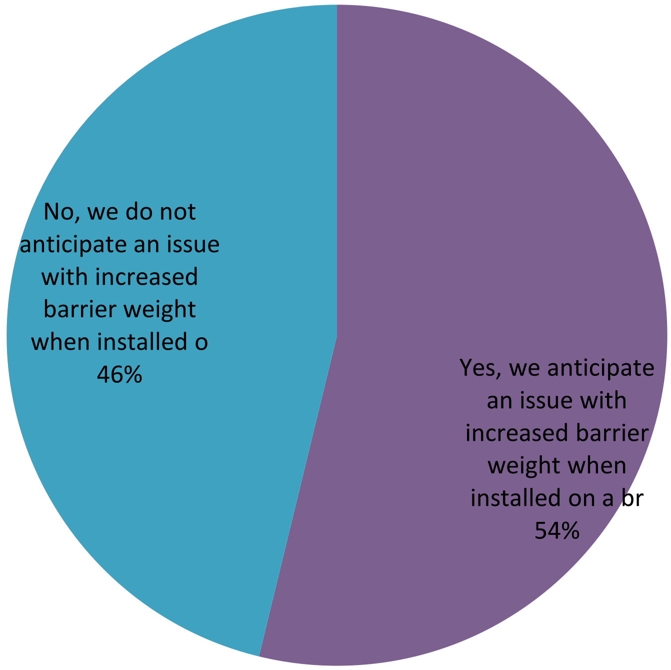


Figure 74. Survey Results for Concern Regarding Increased Weight on Bridge Decks

5.3 Potential Implementation Considerations

Several points of consideration were brought up during internal discussions regarding the PCB concepts and their potential implementation. These considerations included the inspection and repair processes, barrier durability, and the potential variability of friction values between the PCB segments and the supporting surface.

PCB systems need to be inspected to ensure proper installation and barrier performance over the barrier's service life. This inspection process varies depending on the system being inspected but can be generalized to include checks for proper connections and barrier segment integrity. The current F-Shape PCB requires an inspection to verify that each drop-pin has been inserted fully through all of the loops in each connection and that each barrier segment is in good condition for an installation to be complete. Since all the connection components and all the barrier faces are visible from standing near the barrier, the installation process is straightforward. Concept nos. 1, 2, 16, and 17 would require a similar, straightforward inspection process. However, the view of the drop-pins featured in concept no. 18 is obstructed by the steel plates forming the front and back faces of the barrier. In addition, concept no. 19 consisted of barrier segments that interlock and obstruct an inspector's view of the stub of the barrier to verify its structural integrity.

Repairing or replacing pieces of a PCB system was also a consideration that was discussed. While all the PCB concepts allow for the replacement of pieces of the system, some designs require additional effort. Concept nos. 1, 2, and 17 allow for individual barrier segments to be disconnected and replaced without disturbing adjacent segments. Concept no. 18 featured a connection design that requires segments to be slid into place longitudinally, so several segments would need to be adjusted to create room to replace a single segment or connection. Concept nos. 16 and 19 featured staggered segments, so while a top segment could be replaced without disturbing adjacent segments, replacing a bottom segment would require the temporary removal of the two top segments above it.

While increased barrier durability was identified by state DOTs as a desired characteristic, it was not fully investigated in this research phase. The six concepts that were simulated were chosen in part due to their expected potential for increased durability. However, the use of rigid bodies to represent PCB segments prevented direct insight into durability. The following research phase plans to incorporate a more detailed investigation into durability potentially using deformable elements and a focus on a single preferred concept.

Lastly, the friction coefficient used during simulations for the contact between the PCB segments and the supporting pavement may not be conservative in all conditions. A value of 0.4 was selected based on a review of previous research [12]. The 0.4 value was expected to be accurate for PCB segments placed on concrete in fair weather conditions. However, PCB systems can be installed on a range of surfaces and can experience various weather conditions. While MASH currently does not state requirements regarding weather conditions, fair weather would likely result in a higher friction value compared to icy or rainy conditions. Since PCB systems rely on friction as one of the mechanisms for resisting impact forces, it was reasonably concluded that lower friction would result in higher lateral barrier displacements and reduced vehicle safety measurements. The sensitivity of the PCB concepts to friction was not investigated through simulation in this research phase, and thus may be further investigated in a future phase of the effort.

5.4 Discussion

Comparisons of the simulation measurements using MASH safety criteria, including barrier displacement, estimated cost, and barrier weight, were presented to Midwest Pooled Fund Program member states. A survey was distributed to collect feedback on design criteria and request the selection of a preferred design. Design criteria feedback consisted of the need for multiple lifting options, 4 ft of drainage slots per 12.5-ft segment, accommodation for curves with a radius of 100 to 200 ft, and the anticipation of concern with increased barrier weight on bridge decks. As respondents identified concept no. 19 as the most preferred design, it was selected to be developed for full-scale crash testing in the future. Finally, additional considerations for potential PCB system implementation were discussed and will be addressed in future research phases.

Chapter 6 Summary and Conclusions

The objective of this research effort was to analyze candidate PCB concepts and use computer simulations to evaluate the crash performance and feasibility of these concepts. At least one optimized configuration would be recommended for further development and full-scale crash testing in future research phases.

A literature review to identify and review current PCB systems was conducted and funded under an adjacent research effort funded by WisDOT. This review identified common designs and connection types of current PCB systems, as well as their safety performance. Other PCB information that was gathered included barrier segment length, weight, cost, and material type. Alternative concrete materials were reviewed for their potential use in the new PCB design, however, due to the high cost associated with alternative concretes and the lack of current research, the PCB design would be focused on traditional concrete mixes. These alternatives could be further investigated after the new design is implemented.

A survey was distributed to member states of the Midwest Pooled Fund Program to gather input for developing design criteria. This survey was passed on to several PCB fabricators, installers, and consultants to gather their input as well. The survey asked respondents to identify their needs regarding cost, material, durability, installation, safety performance, and anchorage. The design criteria were then established based on the survey responses and the requirement to meet MASH safety criteria. These design criteria consisted of the following:

- Must meet MASH TL-3 safety criteria.

- Should show improved vehicle stability compared to the current F-Shape PCB system.
- Lateral deflection should be limited to 3 ft or less.
- Cost should be less than $100 per linear foot with a focus on increased durability.
- The material should focus on standard concrete, although steel would be considered.
- Connections should be easy to install and inspect.
- Barrier segments should be 32 in. tall, 24 in. wide or less, between 10 to 14 ft long, and segment weight should be limited to 7,000 lb or less.
- The new PCB system should be designed with consideration for placement on curves with a radius of 100 to 770 ft, potential for anchorage, and transition to other barrier types.

Sixteen PCB concept designs were brainstormed and presented to WisDOT as part of the adjacent research effort. The sixteen concepts varied in shape and connection method, with each concept posing several advantages and disadvantages compared to other concepts and existing designs. Of the sixteen concepts, five were selected based on expected performance and feasibility for further development and simulation under this MATC-funded effort. The five selected concepts were:

1. Concept no. 1 – a vertical PCB with a steel plate and drop pin connection
2. Concept no. 2 – a revised version of concept no. 1 with a narrower width and the addition of steel feet
3. Concept no. 17 – a vertical PCB with a steel base plate connection

4. Concept no. 18 – a steel PCB with a nested steel tube and drop pin connection
5. Concept no. 19 – a vertical PCB with staggered and interlocking inverted T-shaped lower segments and inverted U-shaped upper segments

The five selected PCB concepts were simulated using LS-DYNA software to evaluate safety performance and identify any additional concerns with each design. The simulations for the PCB concepts were compared to a validated model of a Midwest F-Shape PCB developed under a previous MwRSF study [11]. The models of the F-Shape PCB and the PCB concepts treated the concrete portion of the PCB designs as a rigid body, which was considered acceptable based on the expectation of no significant damage done to the concrete. Any steel barrier parts or connection hardware were modeled as deformable. The models were created systematically so that comparisons would be direct, and any necessary changes could be easily transferred to other concept models.

Several modifications were made to the PCB concept designs during the modeling process due to either issue that arose in the simulation or the desire to investigate potential design variations. Concept no. 1 was initially simulated with the connection pins arranged in a lateral orientation, and a second version was simulated to study the effect of a longitudinal pin orientation. Concept no. 2 was initially simulated with only one drop pin on either side of the connection, but this caused discontinuity when impacted. A revised model was created with two pins on either side of the connection oriented longitudinally, which alleviated the discontinuity issue. Several simulations for concept no. 17 were conducted with varying impact locations due to vehicle snag which caused numerical instability and error termination in all but one simulation. However, none of the impact locations eliminated the vehicle snag, so the simulation that did not terminate early was used as a comparison. Although it would not result in direct comparison to the other PCB concepts because of the shifted impact location, it was noted that the design would need additional modification to address the vehicle snag issue, and the simulation was considered acceptable for rough comparison. Several variations of concept no. 19 were simulated which investigated the following modifications: an inverted slope on the face of the barrier, a revised stub shape, a narrower width, a shorter segment length, and a shortened stub height. No extra simulations were conducted to investigate modifications to concept no 18.

Based on the initial performance of the concept designs, a sixth concept was selected to be investigated and developed through simulation. Concept no. 16, which shared characteristics with concept no. 1 and concept no. 19, was expected to have acceptable performance due to the satisfactory performance of each of its sister concepts. Two modifications to concept no. 16 were simulated to address barrier tipping concerns and included a larger width and larger steel drop pins.

The simulations were compared by barrier displacement, vehicle stability, MASH safety criteria, estimated cost, and barrier weight. Through these comparisons and the results of the simulations, three concepts were not recommended as viable designs: concept no. 2, concept no. 17, and concept no. 18. Each of these concepts exhibited excessive barrier displacement and raised other concerns regarding cost and vehicle snag. Certain variations of the other three concepts were considered viable designs, as shown in Figure 75, and were recommended as viable concepts for further design and full-scale crash testing in the next research phase. Both variations of concept no. 1 showed acceptable safety performance and improved vehicle stability, and thus, the general design of concept no. 1 was recommended with either pin configuration. The first two variations for concept no. 16 resulted in concerning amounts of barrier tipping, but the third variation adequately corrected this issue. Thus, concept no. 16C was recommended as a viable design. All variations of concept no. 19 resulted in acceptable safety performance, but concept no. 19B showed no positive change in performance, and concept no. 19F resulted in concerning amounts of tipping. Thus, only four variations of concept no. 19 were recommended: concept nos. 19A, 19C, 19D, and 19E.

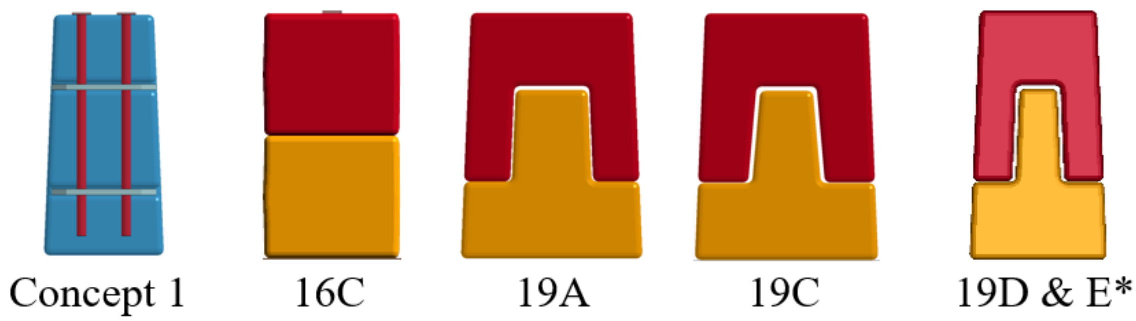


Figure 75. Recommended Concept Designs
(*8-ft segment lengths)

After the recommended concepts were identified, the simulation results and comparison data were presented to members of the Midwest Pooled Fund Program. A survey was then sent to attendees to gather feedback, request design criteria clarifications, and select a preferred concept design. Respondents identified concept no. 19 as the most preferred PCB design, followed by concept no. 1 and concept no. 16 as the second- and third-most preferred designs, respectively. Design criteria for the finalized design were adjusted based on the survey responses. These criteria included:

- The PCB system would need to include multiple options for lifting the barrier to accommodate a wide range of equipment.
- Consideration would be needed for installation on curves with a radius of as little as 100 to 200 ft, potentially through the use of shorter segments.
- Each PCB segment would need to include 4 ft of drainage slots.
- Consideration would be needed for installation on bridge decks where increased barrier weight is of concern.

Conclusions from this research effort will be used in future research funded by the Midwest Pooled Fund Program to develop the selected PCB concept, concept no. 19, into a prototype for full-scale crash testing to MASH TL-3. These future research efforts will develop the finalized design of the new PCB system to comply with all design criteria. It will include the determination of the structural reinforcement design and drainage and lifting accommodations and will prepare the design for implementation in recommended locations.

References

1. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.

2. Ross, H.E., Sicking, D.L., Zimmer, R.A., and Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program (NCHRP) Report No. 350, Transportation Research Board, Washington, D.C., 1993.

3. *Manual for Assessing Safety Hardware (MASH)*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2009.

4. TRB AFB20 Committee, 2016 mid-year meeting (Baltimore, MD) Research Statement Needs https://rns.trb.org/details/dproject.aspx?n=41146

5. Hallquist, J.O., LS-DYNA Keyword User's Manual, Livermore Software Technology Corporation, Livermore, California, 2007.

6. Bielenberg, R.W., Lingenfelter, J.L., Stolle, C.S., Ruskamp, R.J., and Pajouh, M.A., *Development of a New, MASH 2016 TL-3 Portable Barrier System – Phase I*, Report No. TRP-03-460-22, Midwest Roadside Safety Facility (MwRSF), University of Nebraska-Lincoln, Lincoln, Nebraska, January 6, 2022.

7. Silvestri-Dobrovolny, C., Shi, S., Brennan, A., Bligh, R., and Sheikh, N., *Synthesis of the Performance of Portable Concrete Barrier Systems*, National Cooperative Highway Research Program (NCHRP) Report 22-36, Texas A&M Transportation Institute, College Station, Texas, March 2019.

8. Lundstrom, L.C., Skeels, P.C., Englund, B.R., and Rogers, R.A., *A Bridge Parapet Designed for Safety*, General Motors Proving Ground, Presented at 44th Annual Highway Research Board Meeting, January 1965.

9. Michigan Department of Transportation (MDOT) Construction Manual, Chapter 7 – Appurtenances, Available: <https://mdotcf.state.mi.us/public/design/files/english roadmanual/erdm07.pdf> September 11, 2019.

10. Koppa, R.J., *Comparative Study of the Cost of Portable Concrete Barriers for Construction Zones*, Transportation Research Record No. 1056, pgs. 76-90, Transportation Research Board, Washington, D.C., November 1986.

11. Bielenberg, R.W., Faller, R.K., Rohde, J.R., Reid, J.D., Sicking, D.L., and Holloway, J.C., *Development of a Tie-Down and Transition Systems for Temporary Concrete Barrier on Asphalt Road Surfaces*, Report No. TRP-03-180-06, Midwest Roadside Safety Facility (MwRSF), University of Nebraska-Lincoln, Lincoln, Nebraska, February 23, 2007.

12. Bligh, R.P., Sheikh, N.M., Menges, W.L., and Haug, R.R., *Development of Low-Deflection Precast Concrete Barrier*, Report No. FHWA/TX-05/0-4162-3, Texas Transportation Institute (TTI), College Station, Texas, January 2005.

13. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, R.W., Reid, J.D., and Coon, B.A., *Performance Evaluation of the Free-Standing Temporary Barrier – Update to NCHRP 350 Test No. 3-11 with 28" C.G. Height (2214TB-2)*, Report No. TRP-03-174-06, Midwest Roadside Safety Facility (MwRSF), University of Nebraska-Lincoln, Lincoln, Nebraska, October 12, 2006.

14. *LRFD Bridge Design Specifications*, Seventh Edition, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2014.

15. Bielenberg, R.W., Asselin, N.M., and Faller, R.K., *MASH TL-3 Evaluation of Concrete and Asphalt Tied-Down Anchorage for Portable Concrete Barrier*, Report No. TRP-03-386-19, Midwest Roadside Safety Facility (MwRSF), University of Nebraska-Lincoln, Lincoln, Nebraska, April 12, 2019.

Appendix A Selection of Preferred PCB Concept Design Survey

Midwest Pooled Fund Program: Next Generation of MASH TL-3 Portable Barrier System

Introduction

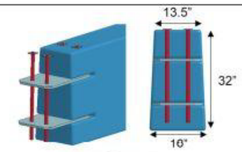
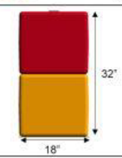
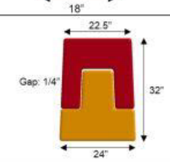
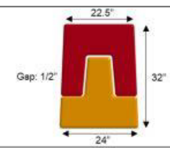
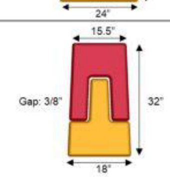
Overview
The Midwest Pooled Fund Program has funded research to develop a new, MASH TL-3 portable barrier system. The objective of this research is to develop a MASH TL-3 compliant portable barrier that improves upon previous designs by significantly reducing free-standing barrier deflections and improving vehicle stability. Design criteria for the new portable barrier include:

- Dynamic deflections less than 36 in.
- 32 in. barrier height
- 24 in. max barrier width
- 10-14 ft segment length
- Up to 7,000 lb segment weight (lifting limit with available equipment)
- Curve installation on 100-770 ft radius

Concepts
An update meeting was held on Friday, September 17, 2021, at 10 am (CST) to discuss design concepts proposed for the MASH TL-3 portable barrier system. The presentation can be downloaded for review at the following link: PCB Pooled Fund Update 9-17-21

The presentation reviewed preliminary simulation analysis of several design concepts. Three concepts were identified as having potential for further development. A summary of those concepts is shown in the table below. Note that Concept 19 had several potential variations that were deemed feasible – Concepts 19A, 19C, and 19D/E. As such, the viable variations of that concept are shown in the table as well. For reference purposes, the current F-shape PCB used by many Midwest Pooled Fund members has a weight of 399 lb/ft and a barrier deflection of 80 in. under MASH TL-3 loading.

Figure A-1. Selection of Preferred PCB Concept Design Survey – Page 1

Concept No.	Maximum Barrier Deflection (in.)	Linear Weight (lb/ft)	Radius Curve (ft)	Profile
1	35	479	~ 100-150	
16	13 (Concept 16-C)	580	~ 800	
19	8.5 (Concept 19-A original concept)	719	~ 1,120	
	13.5 (Concept 19-C revised shear key)	711	~ 490	
	15 (Concept 19-D 12.5-ft segment)	520	~ 720	
	24 (Concept 19-E 8-ft segment)		~ 450	

The presentation also noted that the most effective concepts combined increased mass and improved connection designs to significantly reduce barrier deflection. A preliminary analysis of the use of increased barrier mass suggested that the use of barrier segments with increased weight per linear foot should not be a significant issue for installation of the PCBs on bridge decks, nor would the installation increase bridge deck loading as compared to the current, anchored F-shape PCB installed adjacent to a bridge deck edge.

Purpose
At this time, we are seeking input on preferred designs for further development and clarification of several points relative to the barrier design criteria. The funding for the project only allows for development of 1-2 preferred concepts based on voting. Development will be refined to a single concept during the design phase. Please complete the survey to indicate your states preferences.

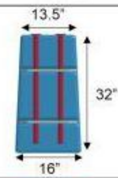
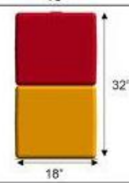
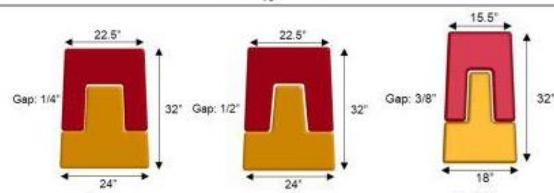
Figure A-2. Selection of Preferred PCB Concept Design Survey – Page 2

1) Contact Information*

Name: ____

Organization: ____

2) Please rank the three proposed design concepts from 1 to 3 with 1 being the highest/most preferred and 3 being the lowest/least preferred.

Concept No.	Profile
1	
16	
19	 A C D/E

*

_______Concept no. 1

_______Concept no. 16

_______Concept no. 19

Figure A-3. Selection of Preferred PCB Concept Design Survey – Page 3

3) A previous survey noted that contractors typically have equipment capable of moving barrier segments up to 7,000 lbs in weight. However, appropriate lifting points will need to be designed into the barrier segments to allow barrier placement. Please indicate below which methods your contractors/installers use to position barrier segments.
*

[ ] Forklift

[ ] Crane

[ ] Front end loader

[ ] Other - Write In: ____

4) In a previous survey, MwRSF has asked states what horizontal curvature needed to be incorporated into the design to deal with roadway curves. The responses received were either that the minimum radius of curvature was unknown or varied widely. Most responses provided fell between 100 ft to 770 ft. Determining the required minimum curvature is important as increased compliance must be designed into the barrier joints, and this compliance increases the barrier deflection.

For example, the current MwRSF F-shape has a curvature radius around 40-50 ft and a deflection of 80 in. The Oregon F-shape barrier has a curvature radius around 110 ft and a deflection of 63.4 in. The proposed barrier concepts have lower curvatures, but also drastically reduce deflection. Please indicate your desired minimum radius of curvature below.
*

( ) 100-200 feet

( ) 200-300 feet

( ) 300-400 feet

( ) 500-600 feet

( ) > 700 ft

5) Drainage or water flow through barrier segments has been noted as a need for portable barriers. However, the amount of drainage required may vary between users. For example, the current F-shape PCB used by many Midwest Pooled Fund members has been configured with two or four 12-in. long slots for drainage. Please indicate your preferred drainage for the new portable barrier concepts below.
*

( ) 1-2 ft of drainage slot per 12.5 ft long barrier segment

( ) 2-4 ft of drainage slot per 12.5 ft long barrier segment

( ) Other - Write In: ____

Figure A-4. Selection of Preferred PCB Concept Design Survey – Page 4

6) As noted previously, MwRSF performed a preliminary analysis of the increased weight of the proposed barrier segments when installed on a bridge deck based on AASHTO Design Case 3. The results found that the increased weight of the new barrier concepts would not be an issue unless installed on large overhangs very close to the deck edge. Additionally, it was found that the current, anchored F-shape PCB demand on decks was actually worse than that of the new barrier concepts due to its proximity to a deck edge. Please review the AASHTO Design Case 3 analysis with you bridge division and indicate whether or not you state anticipates an issue with the barrier dead loading when installed on a bridge deck.
*

( ) Yes, we anticipate an issue with increased barrier weight when installed on a bridge deck

( ) No, we do not anticipate an issue with increased barrier weight when installed on a bridge deck

Comments:

Thank You!

Thank you for taking our survey. Your response is very important to us.

Figure A-5. Selection of Preferred PCB Concept Design Survey – Page 5