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DEVELOPMENT OF A NEW, MASH 2016 TL-3 PORTABLE BARRIER SYSTEM – PHASE I

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16. Abstract

Portable barrier systems are used to redirect errant vehicles through a combination of inertial resistance, lateral friction loads, and tensile loads developed from the mass and friction of the barrier segments. The design of portable barrier systems has evolved over time, but they are primarily comprised of safety-shape, reinforced concrete bodies with various end-to-end barrier connections to transfer load between the barrier segments. Currently, only a limited number of portable barrier designs have met the MASH TL-3 requirements.

A concern with many portable barriers is the large dynamic deflections associated with these systems. Research has attempted to reduce deflections without anchoring the barrier segments, but the effectiveness of this approach is limited without modifications to the barrier segment. Furthermore, research and full-scale crash testing has shown that the sloped face of safety shape barriers causes increased vehicle instability, rollover, and significant vehicle climb. Thus, a new portable barrier design could provide reduced deflection without the use of anchors or other attachments to the road surface as well as allow for more economical and efficient installation of portable barriers.

A literature search of portable barriers was conducted. Different material options for a new portable barrier were researched. Basic design criteria for the new portable barrier system were defined with input from Wisconsin Department of transportation and fabricators. Finally, conceptual designs were proposed and reviewed.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in.	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela per square meter	cd/m^2
		FORCE & PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in.
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yard	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliter	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or “metric ton”)	1.103	short ton (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE & PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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1 INTRODUCTION

1.1 Problem Statement

The basic design of portable work-zone barriers has changed little in recent years. Most non-proprietary portable barrier systems on our nation's highways consist of safety-shape or single slope barrier segments fabricated from reinforced concrete materials. These segments are attached by simple connections that allow the barriers to be easily installed or moved in work zones and for other portable barrier applications. Two general concerns exist with most current portable designs:

1. The segment connections allow high lateral barrier deflections upon vehicle impact, ranging from 19 to 80 in. Where deflections must be limited, anchoring or pinning of the barrier segments into the pavement is required, which impedes installation and removal, exposes workers to traffic hazards, and causes pavement damage.

2. The sloped face of the barrier often allows impacting vehicles to climb and roll as they impact the barrier, causing unstable behavior that can result in rollover.

In 2009, the American Association of State Highway and Transportation Officials (AASHTO) implemented an updated standard for the evaluation of roadside hardware. The new standard, dubbed the Manual for Assessing Safety Hardware (MASH) [1], improved the criteria for evaluating roadside hardware beyond those provided in National Cooperative Highway Research Program (NCHRP) Report 350 [2] through updates to test vehicles, test matrices, and impact conditions. To encourage state departments of transportation (DOTs) and hardware developers to advance their hardware designs, the Federal Highway Administration (FHWA) and AASHTO have collaborated to develop a MASH implementation policy that includes sunset dates for various categories of roadside hardware. Further, the 2009 MASH safety criteria were updated in 2016, resulting in the MASH 2016 document [3]. The new policy required that devices installed on federal-aid roadways after the sunset dates must be evaluated under MASH 2016. Temporary work-zone devices, including portable barriers, are one of the hardware categories that must be successfully tested to MASH 2016. The need to reevaluate existing portable barrier systems developed under previous safety criteria presents an opportunity to develop a high-performance portable barrier system that meets the MASH 2016 safety criteria as well as addresses the deflection and stability concerns of most current portable barrier designs.

A high-performance portable barrier system with a vertical or near-vertical front face would reduce and/or eliminate the potential for vehicle instability, while a modified joint detail could reduce dynamic barrier deflections. In addition, a high-performance portable barrier could be made easier to transport and install as well as offer improved durability through modifications to the barrier geometry, materials, end-to-end connection, and structure.

1.2 Background

The predominant portable barrier system used in work zones are portable concrete barriers (PCBs). PCB systems are used to redirect errant vehicles through a combination of inertial resistance, lateral friction loads, and tensile loads developed from the mass and friction of the barrier segments. The design of PCB systems has evolved over time, but they are primarily comprised of safety-shape, reinforced concrete bodies with various end-to-end barrier connections to transfer load between the barrier segments. Currently, only a limited number of PCB designs have met MASH Test Level 3 (TL-3) requirements. These barriers include the non-proprietary Midwest Pooled Fund F-shape PCB, the New York PCB, the New Jersey PCB, the Texas X-bolt PCB, and the proprietary J-J Hook and Delta Block systems.

A concern with many portable barriers is the large dynamic deflections associated with these systems. Free-standing portable barriers have deflections up to approximately 80 in. Recent MASH TL-3 testing on the F-shape PCB system, previously developed through the Midwest Pooled Fund Program, demonstrated increased dynamic barrier deflection and barrier damage when compared to similar barrier testing under NCHRP Report 350 criteria, as shown in Table 1 and Figure 1. Note that the free-standing barrier deflections for the F-shape barrier increased from 45 in. to almost 80 in.

Table 1. F-Shape PCB Full-Scale Crash Testing [4-6]

Test No.	**Vehicle**	**Mass (lb)**	**Speed (mph)**	**Angle (deg.)**	**Dynamic Deflection (in.)**	**Static Deflection (in.)**
ITMP-2	2000P	4,420	62.3	27.1	45.3	44.9
TB-1	2270P	5,000	61.8	25.7	56.7	56.7
TB-2	2270P	5,000	62.0	25.4	79.6	73.0

Figure 1. F-Shape PCB Deflection and Damage in MASH Testing with 2270P Vehicle [6]

Methods to reduce barrier deflections by pinning, staking, or otherwise tying the barrier to the deck, pavement, or soil have been developed in the past. However, this practice is labor intensive, expensive, and increases worker exposure. Other research has attempted to reduce deflections without anchoring barrier segments, but the effectiveness of this approach is limited without modifications to the barrier segment. Limiting free-standing barrier deflections would allow the barriers to be used more effectively when separating lanes of traffic or vehicles from the work zone because they would not require as much clear area behind the device. Thus, a new PCB design could provide reduced deflection without the use of anchors or other attachments to the road surface as well as allow for more economical and efficient installation of portable barriers.

Research has also shown that the sloped face of safety shape barriers causes increased vehicle instability and rollover, especially with small passenger cars. These studies have shown that 8.5 percent of safety-shape barrier accidents result in rollover, and that safety shape median barriers have over twice the rollover rate of other median barriers. The increased rollover potential with these barrier shapes becomes critical because rollover accidents double the risk of incapacitating and fatal injuries [7].

Full-scale crash testing of safety-shape PCB systems has indicated significant vehicle climb when these barriers are struck by light-truck test vehicles, as shown in Figure 2. Vertical face or near-vertical face, single slope barriers have been shown to provide the largest reduction in vehicle rollover when compared with safety-shape barriers through both computer simulation and full-scale vehicle crash testing. One full-scale crash test of a vertical-shape PCB comprised of steel H-sections demonstrated little to no propensity for the light-truck vehicle to climb the barrier, thus indicating a much lower propensity for causing vehicle rollover. Similarly, a recent MASH test of a single slope concrete bridge rail impacted with a 2270P vehicle conducted at Texas Transportation Institute (TTI) demonstrated little propensity for vehicle climb and improved stability as compared to safety-shape barriers.

Figure 2. Vehicle Climb, Roll, and Pitch Motions with Safety Shape PCB [8]

However, the use of vertical shapes has not been implemented due to the concerns that vertical shapes might increase the lateral loads on impacting vehicles. A review of crash test data has demonstrated that vertical-shape barriers tend to increase lateral vehicle accelerations. However, the increased lateral decelerations do not exceed current safety guidelines for occupant risk. These decelerations should be significantly less for portable barrier systems where moderate barrier deflection is allowed. Vertical-shape barriers would be easier to transport and store, thus increasing the functionality of the barrier. In addition, the use of a vertical shape could potentially decrease both the overall height and width of the barrier. Barrier reinforcement could be made simpler and more consistent throughout the barrier section due to a rectangular shape. Pre-cast vertical barrier segments may also be easier to form than the current safety shapes.

Other issues with available safety-shape PCBs include installation difficulties due to connections and reduced durability. Many current barrier designs have connection hardware that extends from the barrier end, thus making vertical and/or horizontal placement impossible, which limits installation flexibility and efficiency. Additionally, barrier connections that are inefficient to install or require tools are not desired. Finally, the stepped region of safety-shape PCBs concentrates loads to the toes during impact loading and moving operations. However, barrier toes are difficult to reinforce, which promotes damage. A vertical face or near-vertical face single slope barrier could use more consistent barrier reinforcement and provide improved load distribution, which would limit damage and extend barrier life. Thus, a new portable barrier system could address barrier installation, connection, and durability issues and provide an improved user experience.

Portable barriers have traditionally been designed using reinforced concrete as the main structural material. Reinforced concrete is relatively inexpensive and easy to construct. In addition, its relatively high mass aids in vehicle redirection due to inertia transfer between the impacting vehicle and the barrier. However, there are some issues with reinforced concrete as a barrier material. First, reinforced concrete barriers tend to become damaged over time, which requires that barriers be replaced on average intervals of seven to ten years. While the mass of the barrier aids in vehicle redirection, the weight of the reinforced concrete sections can make them challenging to ship and move around in the work zone. Finally, the nature of reinforced concrete structures has limited the type of connection joints that can be utilized.

Thus, there is a need to investigate alternative barrier shapes, connections, and materials to improve portable barrier safety performance, limit dynamic barrier deflections, and reduce and/or eliminate the need for anchoring to the roadway.

1.3 Objective

The objective of this research project is to develop a non-proprietary, high-performance portable barrier capable of meeting the MASH TL-3 safety requirements with reduced free-standing barrier deflections and increased vehicle stability as compared to existing, widely used PCB systems. This high-performance portable barrier could be widely implemented in most applications, and future research could be conducted to further reduce deflections from the baseline design through anchoring or other means. As such, the potential for future anchoring of the barrier to further limit deflections was to be considered during the high-performance portable barrier development. The barrier system was not limited to any certain material or shape. It was desired that the proposed barrier system have a practical length and weight such that typical construction equipment could be used for placement, repositioning, etc.

1.4 Scope

The research to design and evaluate a new high-performance MASH TL-3 portable barrier system will proceed in three phases. Phase I consists of a literature review and the development of design concepts. Phase II will consist of design analysis of preferred concepts and selection of prototype portable barriers for evaluation through full-scale crash testing. Phase III will consist of full-scale vehicle crash testing to evaluate the portable barrier designs selected in Phase I. Only Phase I of the research effort is detailed herein.

Phase I of the research effort began with the collection of background information. A literature search was conducted to investigate previous portable barrier systems for information on barrier shapes, structural design, and joint connections. In addition, the researchers surveyed state DOTs to develop a list of portable barriers that have met the MASH TL-3 requirements, with an emphasis on identifying systems currently in use that eliminate or reduce anchoring to the underlying pavement and/or bridge decks. A limited patent search of portable barriers and connection designs was also conducted to ensure that the new design does not replicate existing technologies. Next, the researchers reviewed potential barrier materials, including steel, reinforced concrete, FRP composites, and others. These materials were investigated to evaluate their feasibility based on structural capacity, fabrication methods, and overall cost. Preferred materials for the new portable barrier system were selected. Finally, the researchers defined the basic design criteria for the PCB system, including cost targets, durability targets, expected barrier impact loads, transportability criteria, and other factors with input from the Wisconsin Department of Transportation (WisDOT) and fabricators.

Concepts for the new portable barrier system were developed by focusing on the areas of barrier geometry, structural design, and barrier connections. The researchers began by brainstorming various concepts for the new portable barrier. Concept development continued with defining the optimal geometry (height, width, segment length, and cross-section) based on a review of previous designs, full-scale crash testing, and surveying fabricators for constructability. The barrier geometry will seek to maximize the safety performance of the barrier while maintaining low cost and durability. Finally, connection concepts were developed that focus on minimizing barrier deflection, simplifying barrier assembly and installation, maintaining low costs, and meeting horizontal and vertical curvature requirements for field installations. Portable barrier concepts developed in the research were presented to WisDOT for review and comment regarding preferred design alternatives for further development. Note that Phase I will not be sufficient to fully develop proposed design concepts and further design and analysis will be required in Phase II.

As noted in Section 1.3, it was anticipated that the design concepts will focus on a barrier design that minimizes deflection while using simple and easy to install end-to-end connections. While this research effort does not include development of tie-down anchorage to the pavement, consideration of future anchorages will be made when developing the portable barrier system in the event that the deflection targets are not met or if further limitation of barrier motion is desired. These anchorage accommodations will be more fully developed in Phase II of the research effort.

2 LITERATURE REVIEW

In the literature review performed for this research effort, previous research into portable barriers was reviewed and summarized. Portable barrier shapes were also analyzed, and in-service performance evaluations (ISPEs) regarding barrier shape were included. Various types of portable barrier connection joints as well as full-scale crash tests of portable barriers were collected and summarized. In addition, simulations of portable barriers were reviewed and included. Finally, alternate concretes were explored. The collected information is shown below.

2.1 Review of NCHRP 22-36

An investigation in PCB systems was performed by TTI and summarized in the NCHRP Project No. 22-36 final report entitled *Synthesis of the Performance of Portable Concrete Barrier Systems* [9]. In NCHRP 22-36, background information regarding PCBs, including shape, connection, anchorage, transportation, installation, and durability were investigated. A survey was sent to state DOTs to gather information regarding current in-use PCB systems. In addition, a survey was sent to PCB manufacturers and contractors regarding manufacture and use of PCB systems. Information garnered from NCHRP 22-36 is summarized in subsequent sections.

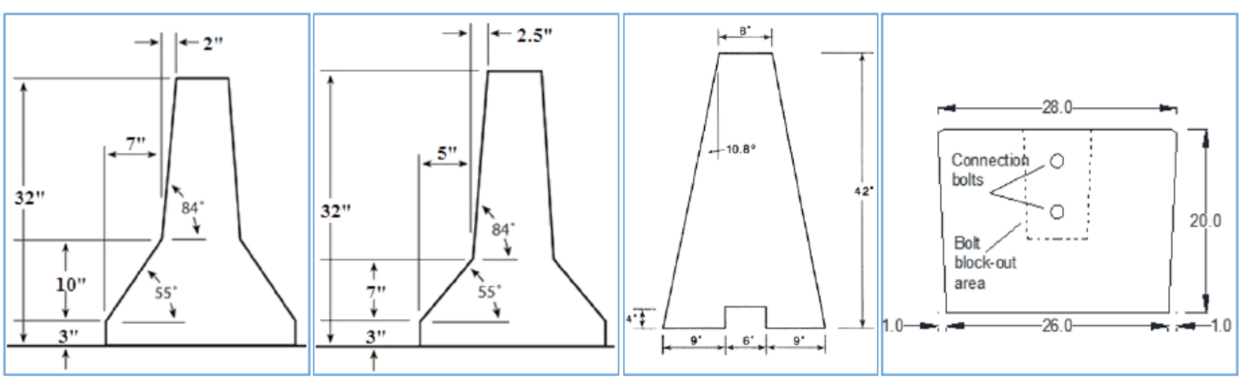
2.1.1 PCB Background Information

NCHRP 22-36 reviewed PCB shape, length, connection, anchorage, transportability, and durability, which are summarized in Sections 2.1.1.1 through 2.1.1.6.

2.1.1.1 Shape

Many PCB shape variations are in use, but most PCB fell under one of four general shapes: New Jersey, F-shape, single slope, or low-profile. Cross section schematics of the New Jersey, F-shape, single slope, and low-profile are shown in Figures 3(a), 3(b), 3(c), and 3(d), respectively.

New Jersey shaped barriers minimize vehicle damage during shallow angle impacts by allowing the tires to connect with the toe and ride up the barrier. During high angle or high-speed impacts, this causes vehicle instability.



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

Figure 3. PCB Profiles: (a) New Jersey, (b) F-Shape, (c) Single Slope, and (d) Low-Profile [9]

The F-Shape barrier was designed to reduce vehicle instability by lowering the height of the toe as compared to the New Jersey barrier geometry. Full scale crash tests found the F-Shape barrier performed significantly better than the New Jersey shape with regards to vehicle climb, post-crash trajectory, and vehicle roll for vehicles with high centers of gravity [10-12].

According to the NCHRP 22-36 report, the 10.8-degree single slope barrier system performs comparably to the New Jersey shaped barrier system. The barrier performed acceptably under NCHRP Report 230 [13] criteria.

The low-profile barrier shape is used in low-speed work zones and modifications were implemented for high-speed applications. At the time of publication of NCHRP 22-36, the low-profile barrier was tested to TL-2 criteria and researchers at TTI were conducting TL-3 testing. The TL-3 evaluation of the low-profile barrier has since been completed and is summarized in *MASH TL-3 Evaluation of the TxDOT TL-3 Low-Profile Barrier for High-Speed Applications* [14]. Low profile barriers have one distinct advantage over taller barriers in that they provide improved sight lines. Taller barriers obstruct driver eyesight and block headlights at night.

Vertical barriers were not discussed in NCHRP 22-36, but this geometry has been applied successfully in permanent barrier designs. Barriers featuring this shape result in low vehicle roll, pitch, and yaw angles, and reduced vehicle climb, but may have increased lateral acceleration forces compared to New Jersey and F-shape barriers [10]. Vertical barriers, as shown in Figure 4, do not feature the lower sloped face that is present on New Jersey and F-shape barriers.

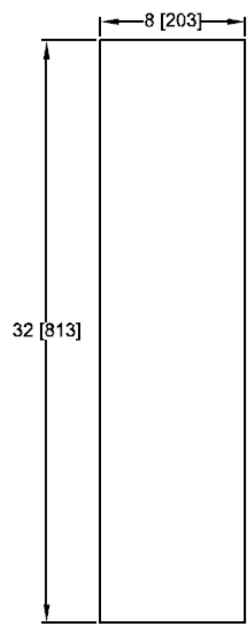


Figure 4. Vertical PCB Profile Dimensions in. (mm) [10]

2.1.1.2 Length

The length of portable barrier segments typically varied between 10 ft to 30 ft. Segment length is important as it affects segment mass and the number of barrier connections or joints in the barrier system. Portable barrier system deflection is largely dependent on segment length, barrier weight, connection, and anchorage. Shorter barrier segment lengths have lower barrier mass and require more connections. Both factors tend to increase barrier deflection as segment length is reduced.

2.1.1.3 Connection

The type of connection utilized in a PCB system largely affects degree of rotation at the barrier joints and the corresponding deflection of the barrier segments. Slack, rotation, and/or deformation at the joint connections allows increased relative motion between the barrier segments and results in higher barrier deflections. Connections which are tight tolerances and higher tensile, moment, and shear continuity will limit motion between barrier segments and minimize barrier deflections during impact. Manufacture and installation of PCBs must also be taken into consideration when designing the barrier connection. For example, the X-bolt connection, designed by TTI, is a barrier joint connection with high level of continuity due to its use of tensioned threaded rods which are installed in a “x” pattern across the barrier joint. This resulted in 19 in. and 27 in. deflections for 30-ft and 10-ft segment lengths, respectively, when tested to MASH TL-3 [15, 16]. However, this connection requires tools and hardware to install, resulting in its infrequent use.

2.1.1.4 Anchorage

NCHRP 22-36 noted a series or methods that have been used to anchored PCB to limit barrier deflections. Various methods to anchor systems to the pavement exist, including vertical or angled pins driven into the pavement, through bolts, and backup plates. Examples of some of these systems are shown in Figure 5. Furthermore, the number of anchors applied to a barrier segment can vary.

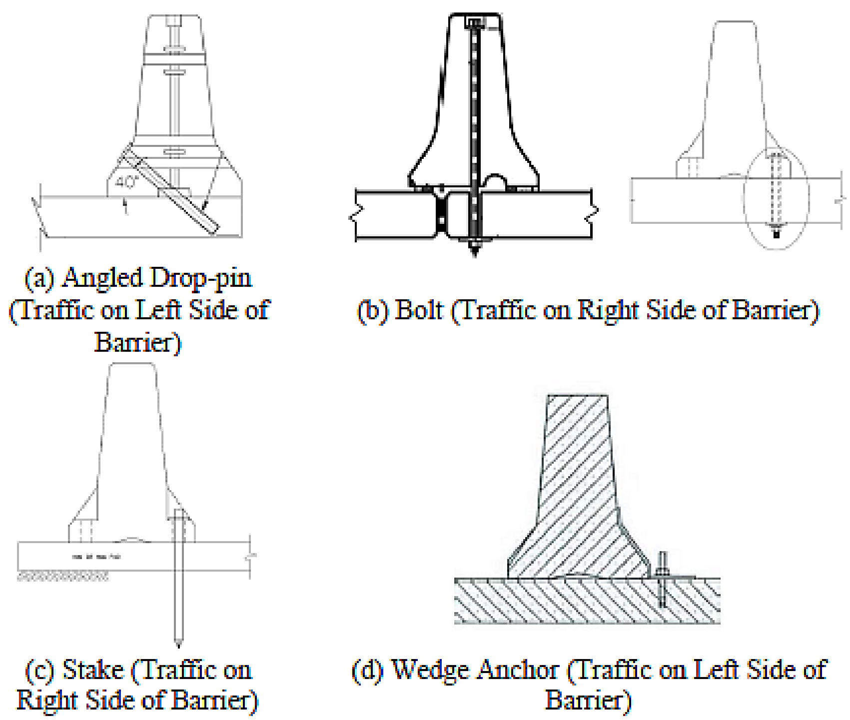


Figure 5. PCB Anchorage: (a) Drop-Pin, (b) Bolt, (c) Stake, and (d) Wedge Anchor [9]

2.1.1.5 Transportation

Transportation of PCBs can be costly and time consuming due to their weight, size, shape, and required quantity. Trailers have a maximum load weight limit, therefore the number of PCBs per load will be limited by PCB weight, which ranges between 4,800 lb to 20,000 lb, depending on the type of barrier [9]. Furthermore, the number of PCBs per load will be limited by trailer size and PCB size. TTI noted a common trailer size of 40 ft long and 7½ ft wide to perform an analysis. The approximate weight of each type of barrier, for sections lengths of 10 ft, 12.5 ft, 20 ft, and 30 ft, are shown in Table 2.

Table 2. Approximate Weight of Barriers by Shape and Section Length [9]

Barrier Shape	**Approximate Barrier Weight (lb)**			
	Length (ft)			
	10	**12.5**	**20**	**30**
New Jersey	4,750	5,950	9,500	14,300
F-Shape	4,800	6,000	9,650	14,500
Single Slope	6,800	8,500	13,600	20,400
Low-Profile	5,100	6,500	10,750	16,350

A common width for PCBs is 24 in., which was assumed for each of the four barrier shapes to calculate the number of barriers carried by a single trailer. The number of barriers which can be carried on a common trailer are shown in Table 3.

Table 3. Number of Barriers Carried by Common Trailer [9]

Barrier Shape	**Number of Barriers Carried by Common Trailer**			
	Length (ft)			
	10	**12.5**	**20**	**30**
New Jersey	9	7	4	3
F-Shape	9	7	4	3
Single Slope	6	5	3	2
Low-Profile	8	6	4	2

2.1.1.6 Durability

PCBs can be damaged during transportation, installation, or if impacted while in use. Durability of PCBs at each of these stages has not been investigated, therefore no information regarding reduced maintenance or repair and associated cost is available. Furthermore, no information existed to calculate the life expectancy for PCBs.

2.1.2 Non-Proprietary PCB MASH Test Nos. 3-11 and 4-12

Full-scale crash tests performed according to MASH test designation nos. 3-11 and 4-12 were collected and summarized in the NCHRP 22-36 report. All tests listed in the NCHRP 22-36 report were included in this report and are listed in Section 2.4.

2.1.3 Survey of State Practice and Satisfaction with PCB Systems

For NCHRP 22-36, a survey was sent to state DOTs throughout the USA and the DOT for Ontario, Canada, requesting information regarding portable barrier systems. A total of 40 responses were received, identifying 52 currently in-use PCB systems. PCB shape was collected from the responding DOTs. The PCB shape distribution revealed a total of 25 F-shape, 23 New Jersey, two Single Slope, and two Other (modified New Jersey and low-profile) PCB systems in use, as shown in Figure 6.

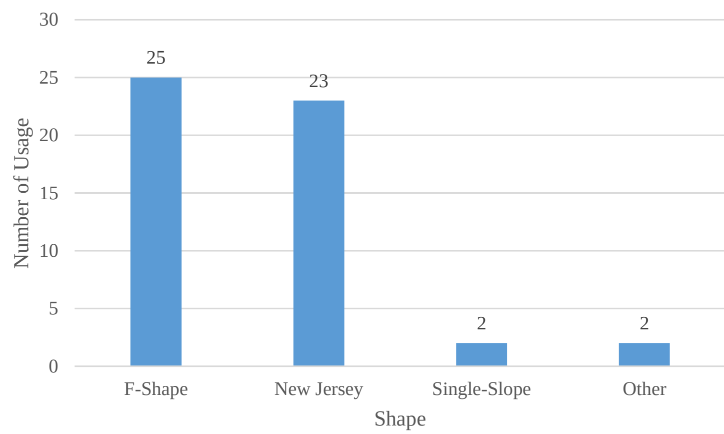


Figure 6. PCB Shape by Usage Number [9]

Segment length was also collected. Results found a total of fifteen PCB systems which featured 10-ft segments, four with 12-ft segments, thirteen with 12.5-ft segments, eleven with 20-ft segments, two with 30-ft segments, and seven with other or unknown segment lengths, as shown in Figure 7.

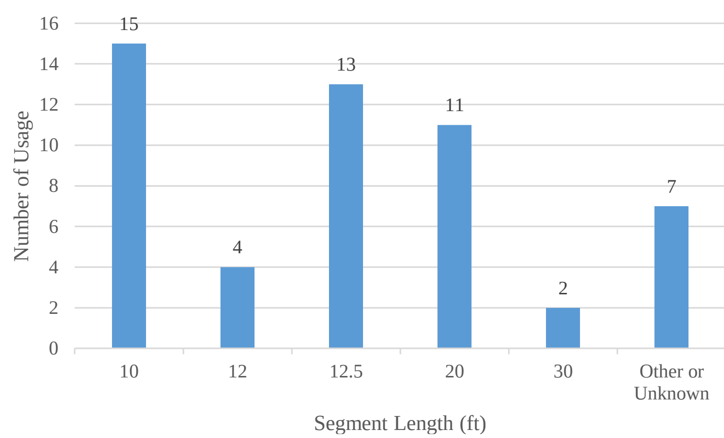


Figure 7. Segment Length by Usage Number [9]

The connection type for each PCB was requested through the survey and is summarized in Figure 8. A total of 39 PCB systems utilized the pin and loop connection, seven utilized JJ-Hooks, three utilized X-Bolt, one utilized connection plates, and five utilized some other type of connection. The other connection types were doweled and grouted (Arizona DOT), connection key (New Jersey DOT), Type T connection (Ontario DOT), beam stiffener (New York DOT), and connection rods (Texas DOT).

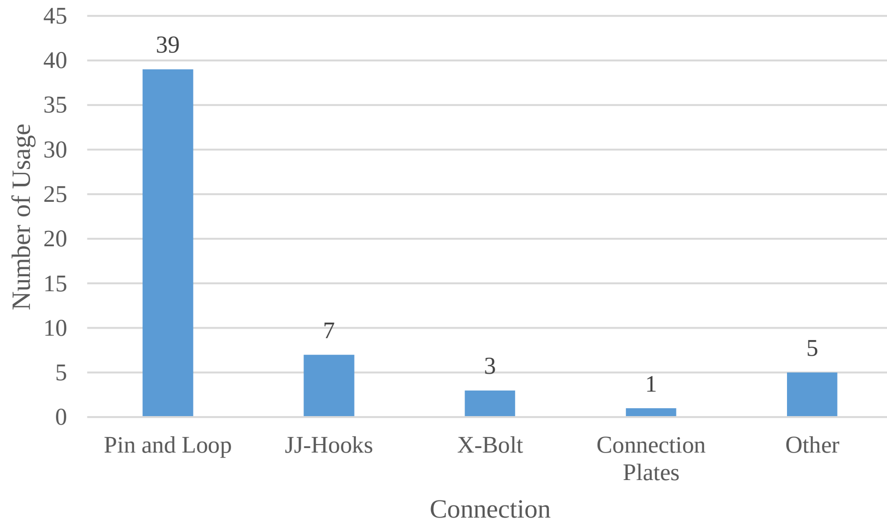


Figure 8. PCB Connection by Usage Number [9]

PCB systems can be installed for temporary or permanent applications. The survey found that the distribution of temporary PCB applications consisted of 26 free-standing, seven pinned, 13 bolted, 19 staked, and seven other applications. Permanent applications consisted of seven free-standing, four pinned, two bolted, seven staked, and two embedded applications. This information is shown in Figures 9 and 10, respectively.

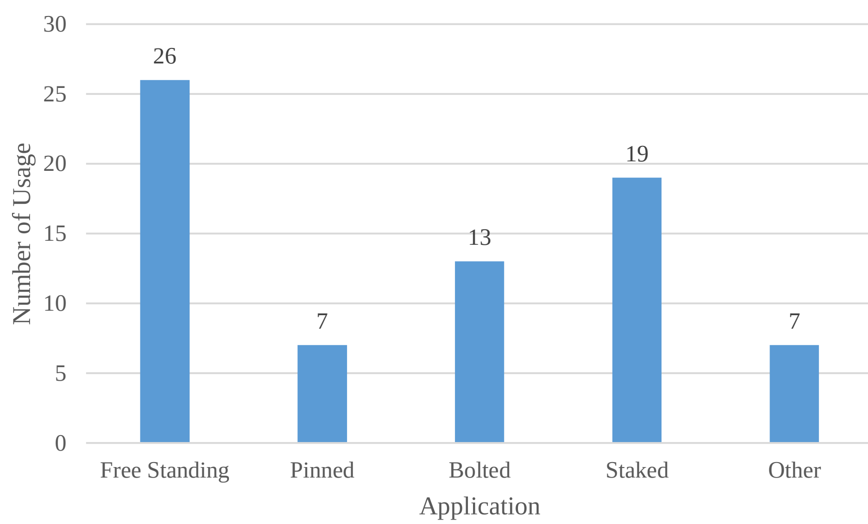


Figure 9. Temporary PCB Application Type by Usage Number [9]

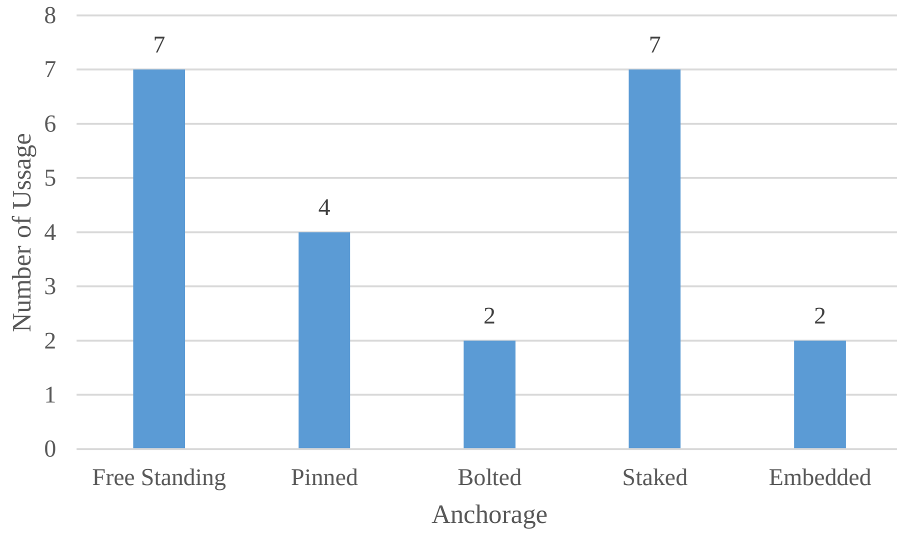


Figure 10. Permanent PCB Application Type by Usage Number [9]

The type of pavement PCB systems were installed on is shown in Figure 11, with two on asphalt only, 50 on concrete and asphalt, and 18 on other.

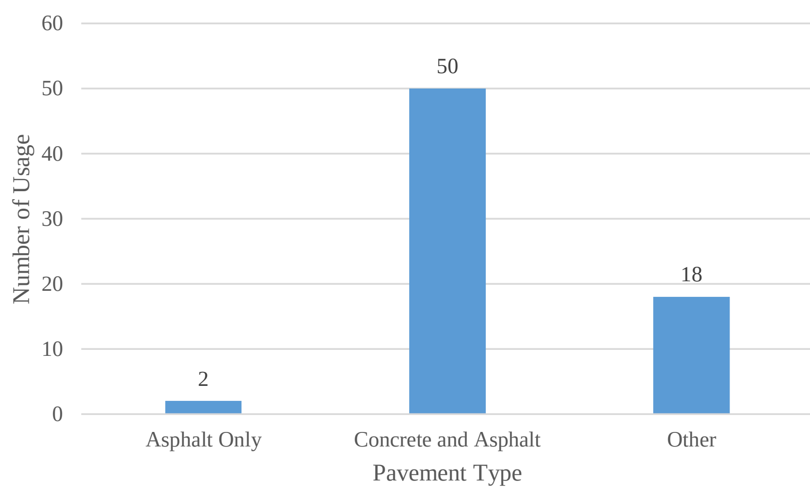


Figure 11. Pavement Type by Usage Number [9]

Satisfaction with installation and removal of PCB systems was collected and shown in Figures 12 and 13, respectively. When questioned about satisfaction with PCB inspectability, 29 systems were rated satisfied, eighteen were neutral, and five were dissatisfied, as shown in Figure 14. Inspectability includes ensuring the system has been installed correctly and evaluation of barrier damage and condition. State DOTs were also asked to rank their satisfaction with regard to transportability of their PCB systems. This information is shown in Figure 15 for the various segment lengths. Satisfaction with regard to durability was also requested and is shown in Figure 16 for the four PCB shapes.

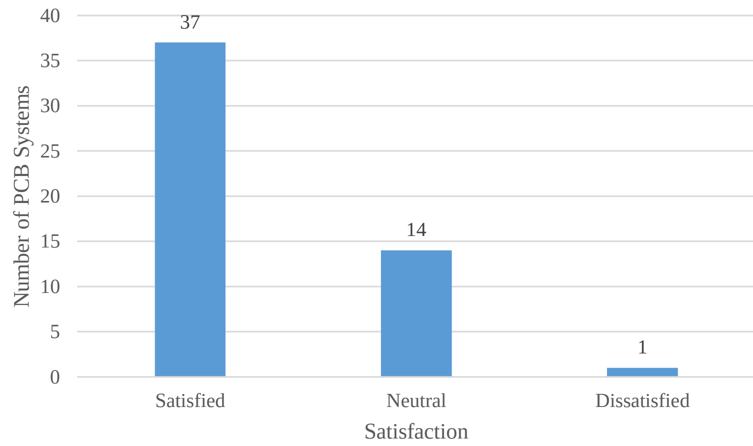


Figure 12. Number of PCB Systems by Satisfaction with Installation [9]

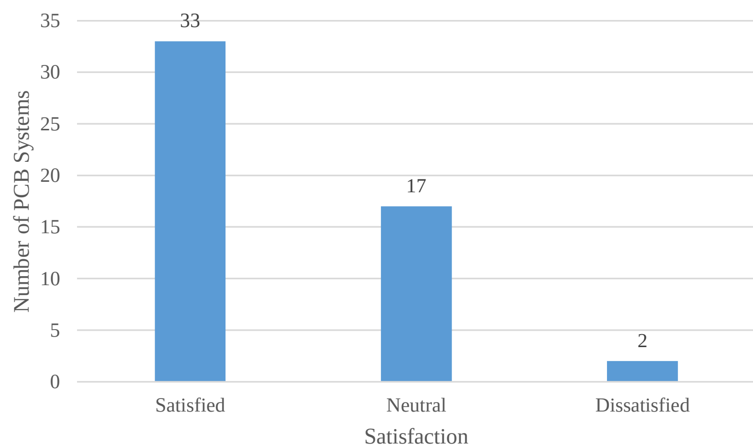


Figure 13. Number of PCB Systems by Satisfaction with Removal [9]

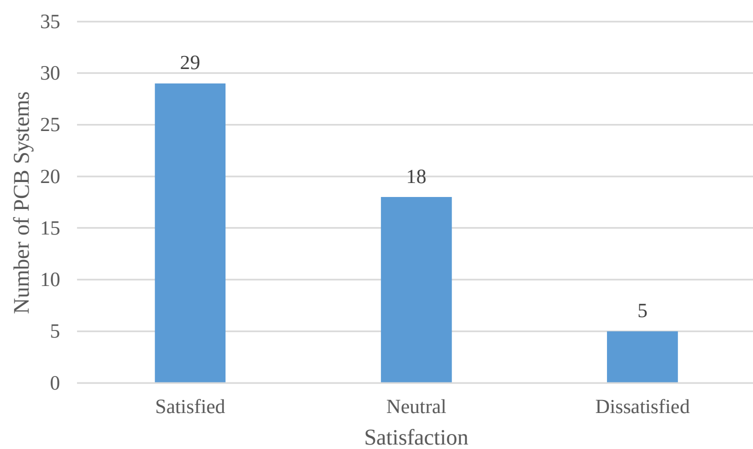


Figure 14. Number of PCB Systems by Satisfaction with Inspectability [9]

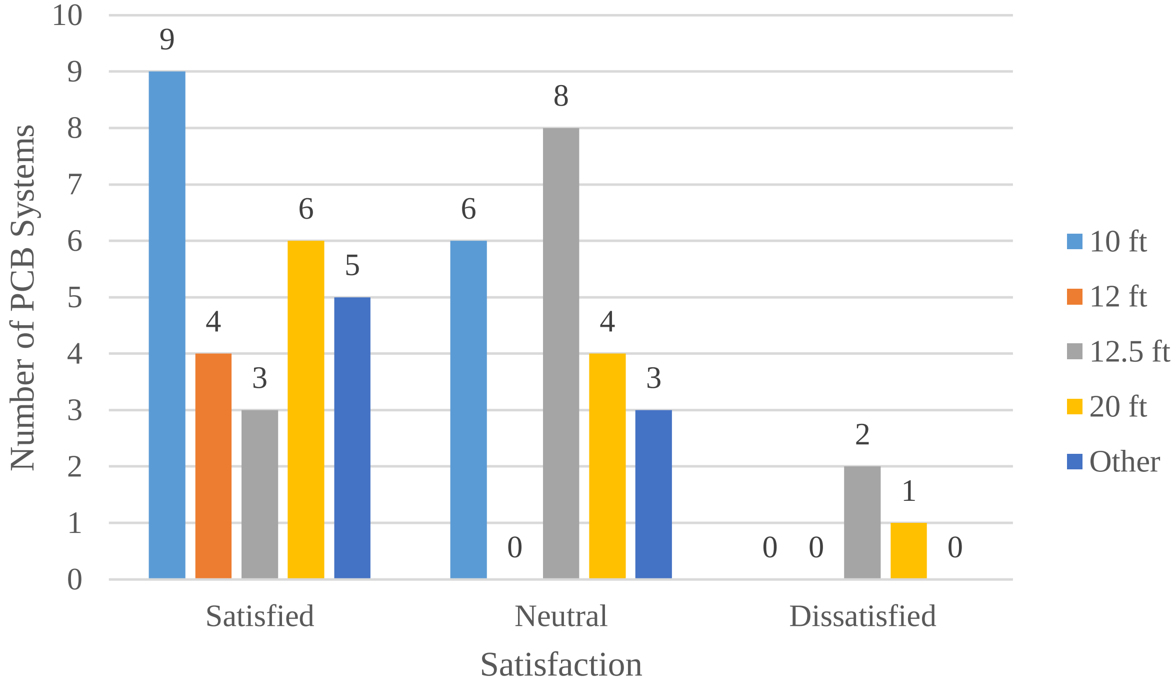


Figure 15. Number of PCB Systems by Satisfaction with Transportability and Segment Length [9]

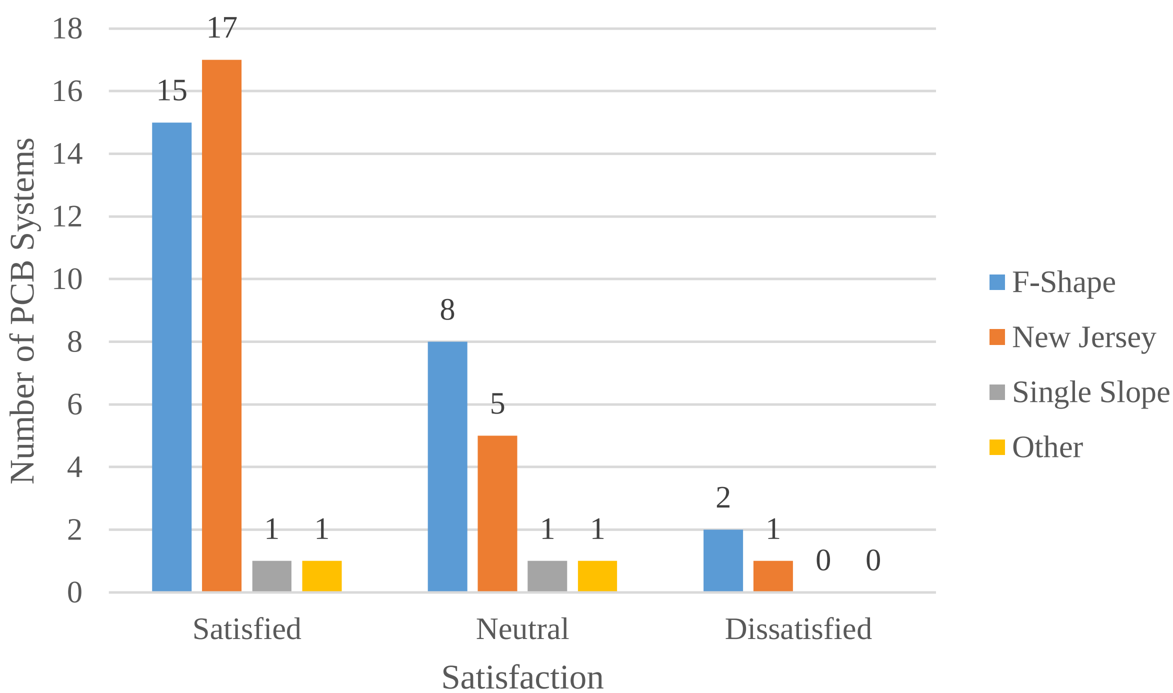


Figure 16. Number of PCB Systems by Satisfaction with Durability and Shape [9]

DOT agencies were asked whether they would adopt a new MASH PCB design. The responses are shown in Figure 17; 20 DOTs responded yes, 10 responded no, and 9 responded with unknown.

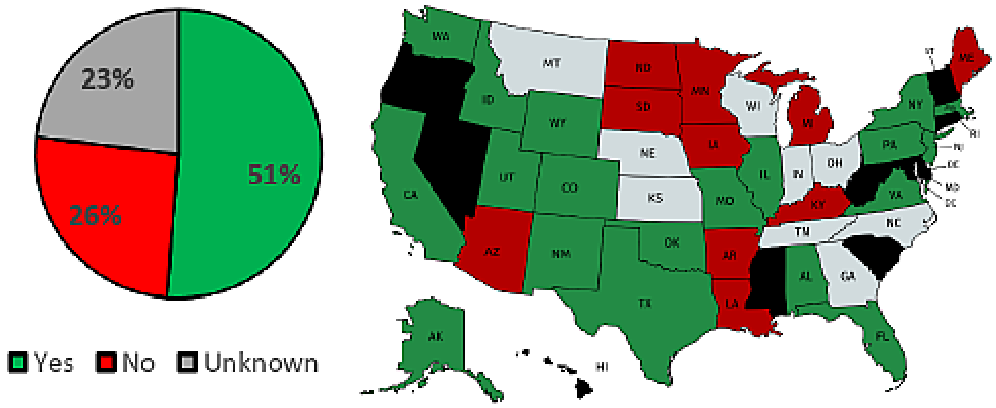


Figure 17. DOT Agency Plans to Adopt a New MASH PCB System [9]

Furthermore, DOT agencies were asked if they had other requirements or desired characteristics for a new PCB system. A total of 17 agencies responded yes and 22 responded with unknown, as shown in Figure 18. The responding agencies suggested reduced deflection, lighter barriers (possibly made of steel rather than concrete), allowing for top attachments, designing for possible permanent installation, and permitting placement on sharp curves.

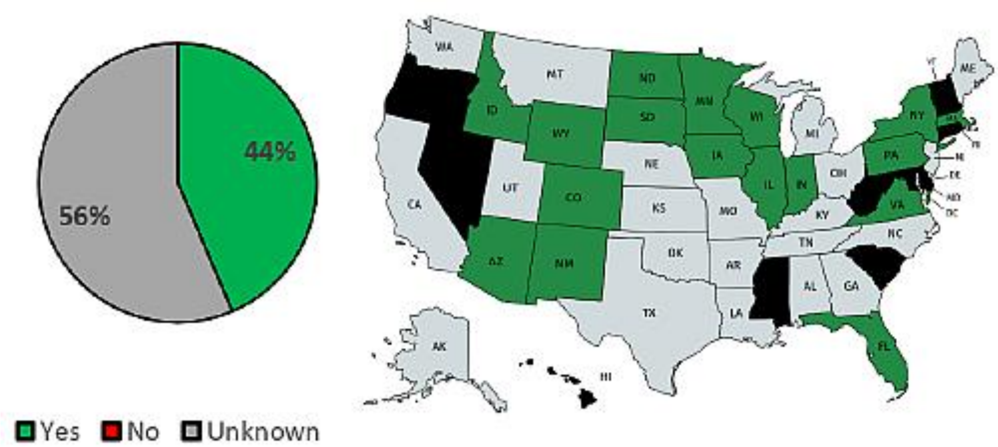


Figure 18. Other Requirements for a New PCB System [9]

2.1.4 Survey of Manufacturers and Contractors

For NCHRP 22-36, various manufacturers and contractors were contacted and questioned regarding PCB systems. Advantages and disadvantages were identified in terms of construction, durability, transportability, installation, removal, and inspectability.

Regarding the manufacture of PCBs, the single slope geometry was rated the easiest due to the constant tapered profile. The single slope PCB was also rated highest in durability due to toe chipping in F-shape and New Jersey PCBs. Manufacturers noted a solution to this problem would be to reinforce the toes with steel rebar, but this would increase manufacturing costs.

The JJ-Hook connection was the most preferred connection type by manufacturers based on ease of installation and removal, ease of inspection, and durability. Pin and loop connections were regarded well in the survey except for issues with installation due to the loops being different on each end of the barrier. The X-bolt and connection plate type connections were rated lower due to increased installation difficulty and the need for additional connection hardware and tools.

Manufacturers preferred shorter segment lengths due to easier transport of the PCBs by truck as shorter lengths allow for more segments per truckload and smaller equipment for loading and unloading.

Anchorage types were also ranked, with the pinned at an angle being the highest preferred, followed by staked, then bolted, and lastly embedment. Rankings were generally based on ease of installation. For pinned and staked, a hole must be drilled in the concrete for installation. Bolted anchorage requires epoxy. When installing an embedded anchor, excavation and backfill are required.

2.1.5 NCHRP 22-36 Future Research Recommendations

Suggestions for a new PCB system based on information gathered from DOTs, manufacturers, and contractors, include design for low deflection, reduced weight, ability to follow curves, drainage features, and allow for top attachments. Furthermore, consideration for TL-4 or TL-5 was also suggested. Finally, a non-proprietary crash cushion for the barrier ends was mentioned. It was also desired that the new PCB system meet performance needs set by DOT agencies while meeting constructability constrains for manufacturers and contractors.

2.2 Portable Barrier Shapes

Shapes of portable barriers have evolved from the original GM shape, described below, due to in-service performance evaluations and full-scale crash testing. Currently, three general shapes for PCBs exist: safety shape, single slope, and vertical. Safety shape barriers include the GM shape, New Jersey Shape, and the F-shape.

2.2.1 GM

General Motors developed the GM shaped concrete barrier, which features a shallow lower slope and steep upper slope, as shown in Figure 19. The overall height is 32 in., with a 2-in. tall reveal, a 13-in. tall lower sloped face, and a 17-in. tall upper sloped face. The lower sloped face has a 55-degree angle and the upper sloped face has an 80.4-degree angle.

The GM shape was designed to allow vehicles impacting at lower speeds and angles to climb the lower sloped face and be redirected while limiting the amount of vehicle sheet metal contacting the barrier and becoming damaged [17]. In crashes at higher speeds and angles, the upper slope redirects the vehicle. The GM shape barrier and its descendants (New Jersey and F-shape) are called safety shaped barriers.

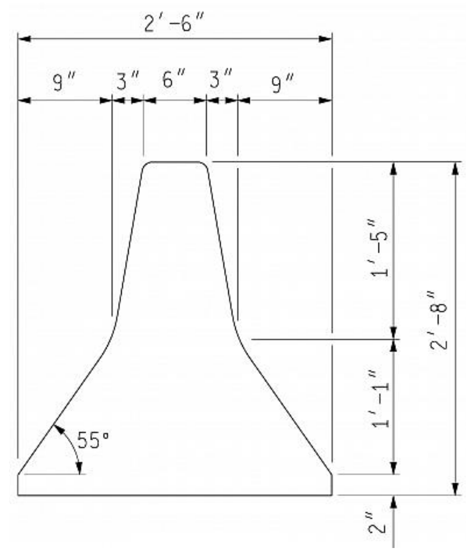


Figure 19. GM Shape PCB [18]

2.2.2 New Jersey

The New Jersey barrier, shown in Figure 20, was developed by the New Jersey DOT in the early 1960s [19, 20]. The lower sloped face features a 55-degree angle and a height of 10 in. with a 3-in. tall reveal at the bottom. The upper sloped face is 19 in. tall at an angle of 84 degrees. The overall barrier height is 32 in., but a 42-in. tall version also exists. This design was developed over many years of crash testing.

Like the GM shape barrier, the lower sloped face allows the vehicle to climb the barrier, resulting in lower impact forces and accelerations and minimized sheet metal damage. Consequently, at high impact angles, vehicle climb on the lower sloped face can lead to increased vehicle climb and roll angles, which can potentially lead to vehicle instabilities and rollover.

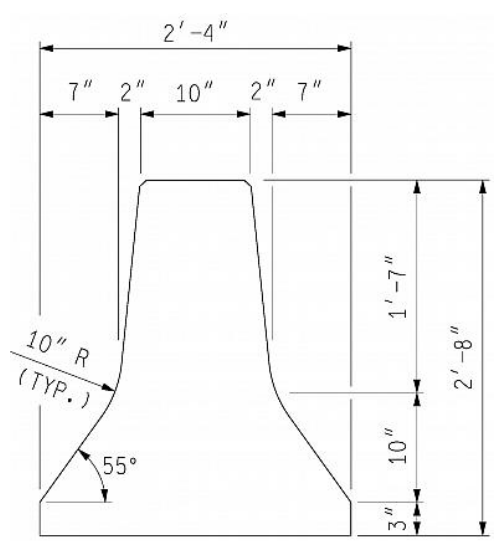


Figure 20. New Jersey Shape PCB [18]

2.2.3 F-Shape

The F-shape barrier, shown in Figure 21, was developed to reduce vehicle climb and roll seen in New Jersey barriers. Six variations, named A through F and based on the New Jersey shaped barrier, were developed and analyzed using computer simulations [21]. The F-shape design exhibited reduced vehicle climb and roll as compared to the New Jersey shape and featured the shortest lower sloped surface.

This barrier features a 3-in. tall reveal, a 7-in. tall lower sloped face at an angle of 55 degrees, and a 22-in. tall upper sloped face at an angle of 84 degrees. The overall height of the barrier is 32 in. and the width is 24 in.

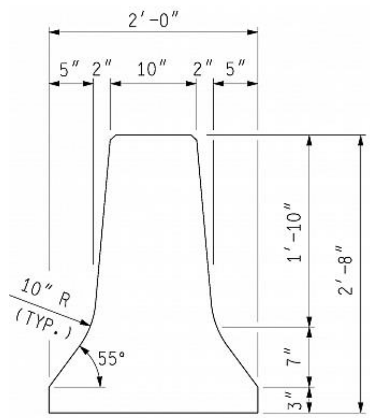


Figure 21. F-Shape PCB [18]

2.2.4 Vertical

Vertical barrier geometry, shown in Figure 22, leads to impact forces that act normal to the barrier face, and therefore, a vertical barrier results in only horizontal forces. This reduces vehicle climb and roll, resulting in more stable vehicle redirection. However, peak lateral impact forces tend to increase with the vertical barrier shape. Additionally, because the vehicle does not climb the barrier face, it does not roll away from the barrier and may result in head slap, which occurs when lateral impact forces cause the passenger’s head to be ejected through the side window of the vehicle and contact the barrier [22].

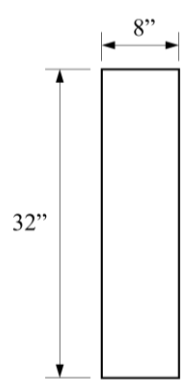


Figure 22. Vertical Shape PCB

2.2.5 Single Slope

The lower sloped surface and reveal present on safety shape barriers were eliminated in the single slope design, as shown in Figure 23. This results in improved vehicle stability during high-angle impacts [23]. Variations of the single slope barrier exist, with varying face angles and overall barrier heights, including the Texas SSCB and the California Type 60, as shown in Figures 24(a) and 24(b), respectively. The Texas SSCB barrier features a sloped face at 10.8 degrees from vertical and the California Type 60 barrier features a sloped face at 9.1 degrees. Single slope barriers were designed to balance impact forces and vehicle roll.

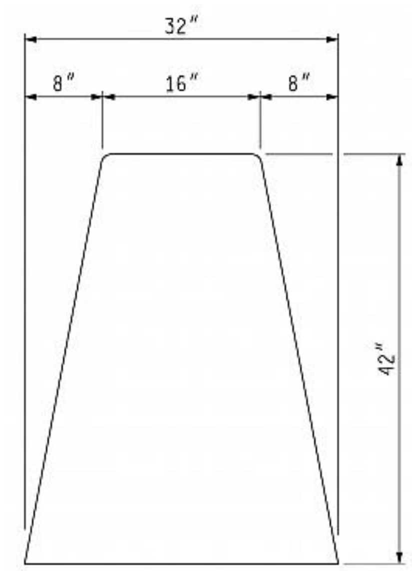


Figure 23. Single Slope Shape PCB [18]

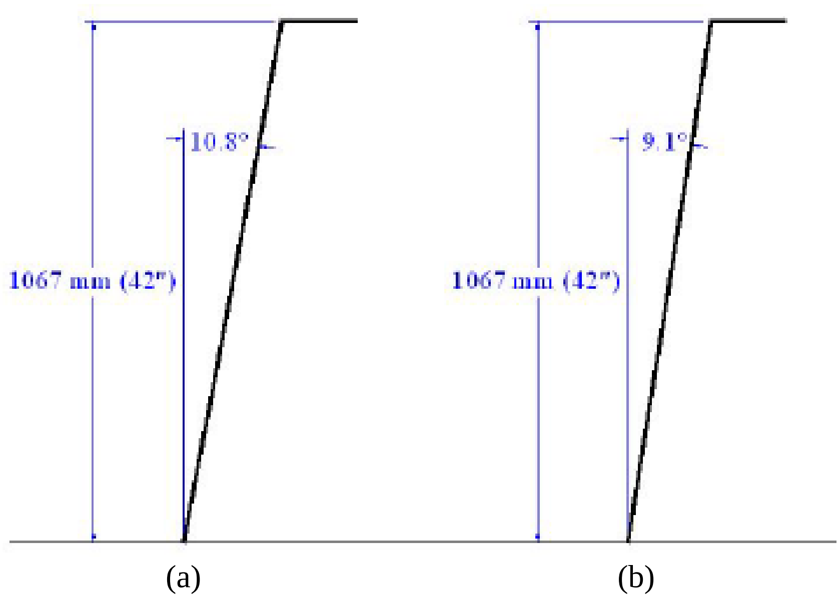
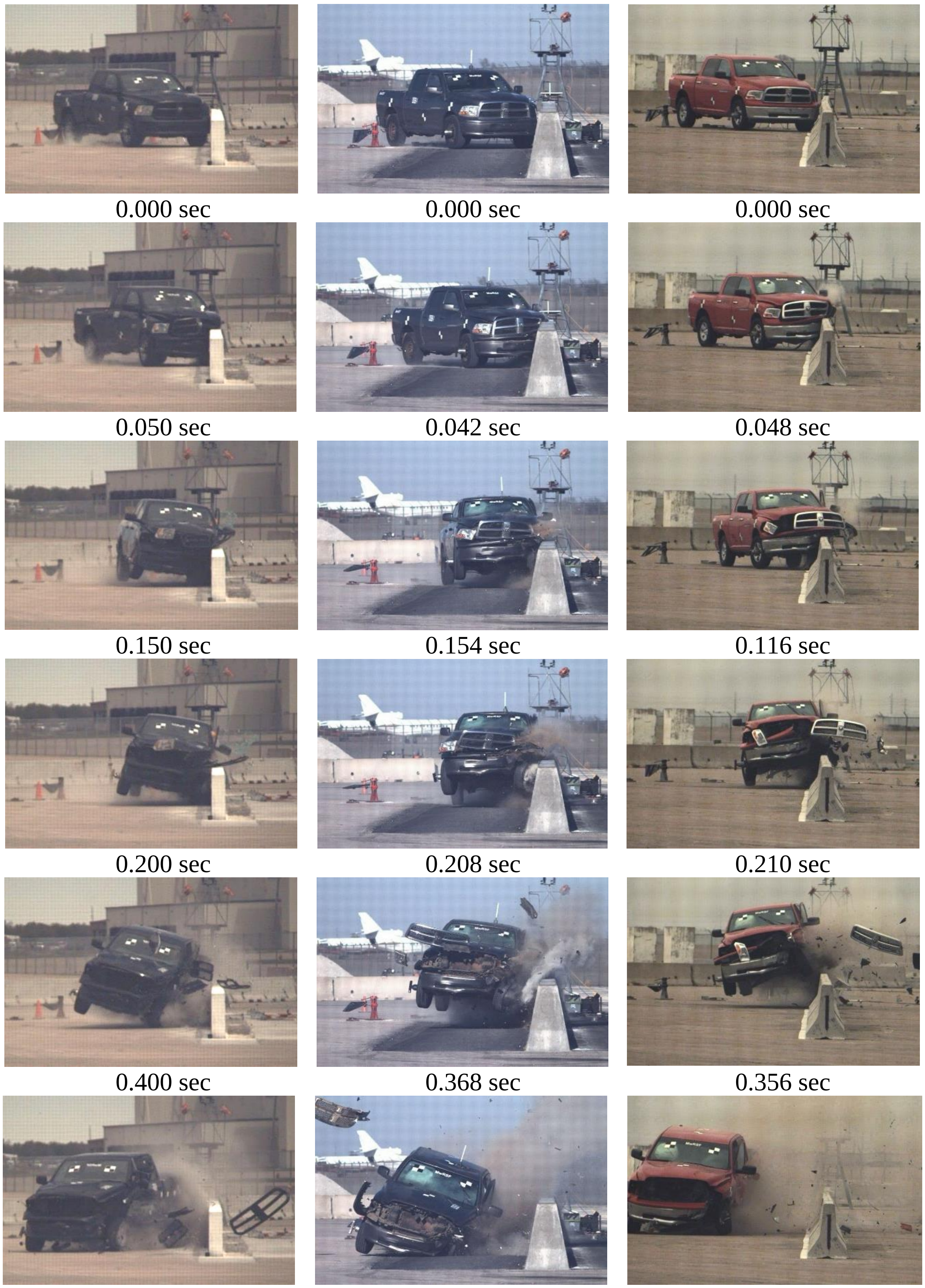


Figure 24. Single Slope PCBs: (a) Texas SSCB and (b) California Type 60 [22]

2.2.6 MASH Test No. 3-11 Testing of Vertical, Single Slope, and New Jersey Shape Barriers

MASH TL-3 full scale crash tests with the 2270P vehicle have been performed on vertical, single slope, and New Jersey shape barriers. Test no. H34BR-2 was performed on a 34-in. tall permanent vertical concrete bridge rail [24] and sequential photographs of the test are shown in Figure 25(a). A permanent single slope barrier with a height of 42 in. was evaluated in test no. OSSB-1 [25], as shown in Figure 25(b). The 32 in. tall New Jersey shape portable barrier bolted to the pavement was evaluated in test no. NJPCB-2, as shown in Figure 25(c) [26]. Test results, including roll, pitch, yaw, and impact severity (IS) collected during each test are shown in Table 4. Comparison of these tests found that vehicle stability was significantly increased with the vertical shape barrier. Occupant ridedown accelerations and occupant impact velocities for all three barrier shapes were within MASH limits. Similar results have been observed for 1100C small car testing under MASH.



(a)	(b)	(c)
0.000 sec	0.000 sec	0.000 sec
0.050 sec	0.042 sec	0.048 sec
0.150 sec	0.154 sec	0.116 sec
0.200 sec	0.208 sec	0.210 sec
0.400 sec	0.368 sec	0.356 sec
0.650 sec	0.724 sec	0.934 sec

Figure 25. Comparison of (a) Vertical [24], (b) Single Slope [25], and (c) New Jersey [26] Shape

Table 4. Vertical, Single Slope, and New Jersey Shape Barrier Test Results [24-26]

Test No.	Barrier Shape	Roll (deg.)	Pitch (deg.)	Yaw (deg.)	IS (kip-ft)
H34BR-2	Vertical	13.7	-2.8	-44.9	126.4
OSSB-1	Single Slope	-20.0	6.6	29.3	116.3
NJPCB-2	New Jersey	20.7	-12.0	30.1	112.6

2.2.7 ISPE of Safety Shape vs. Vertical Barriers

An ISPE of safety shape and vertical shape concrete barriers was performed by MwRSF in 2011, which utilized crash data from the state of Iowa [27]. The objective was to determine which barrier profile resulted in lower injury levels and lower rollover propensity.

It was found that crashes involving safety shape barriers resulted in higher injury levels compared to crashes involving vertical shape barriers. It was also found that rollovers are twice as likely to occur during crashes which involve safety shape barriers compared to vertical barriers. This study recommended the expanded use of vertical barriers.

Safety shape and vertical barriers were the only barrier shapes evaluated in this ISPE. The safety performance of single slope barriers was not considered because they were not in use on state owned highways in Iowa.

2.2.8 Vehicle Rollovers and Impact Forces

According to *An Analysis of Motor Vehicle Rollover Crashes and Injury Outcomes* [7], a report published by the National Highway Traffic Safety Administration (NHTSA), approximately one third of vehicle fatalities resulted from rollover crashes. Furthermore, fatalities are more likely to occur in rollover crashes compared to non-rollover crashes. While rollover crashes are the least frequent type of crash, they result in serious and fatal injuries more often than other types of crashes. The fatality rate for rollover crashes is second only to frontal crashes, resulting in approximately 10,000 deaths a year [28]. It was also found that eight percent of rollover crashes result in occupant ejection [22].

To determine the effects of impact speed, impact angle, and barrier geometry on vehicle rollover propensity, a simulation study was performed in 1990 [11]. Impact speeds ranged between 30 and 85 mph and impact angles ranged between 5 and 25 degrees. Four barrier shapes were evaluated: safety shape, F-shape, single slope, and vertical.

The general findings from this simulation study were:

- The F-shape barrier offers little performance improvement over other concrete safety-shaped barrier for these impact conditions.
- The constant sloped barrier with an 80-degree slope offers some rollover reductions while slightly increasing lateral vehicle accelerations.
- The vertical wall barrier offers the greatest reduction in rollover potential, but with the greatest increase in lateral accelerations.

A study to develop vertical faced concrete median barriers with head ejection criteria was performed at MwRSF in 2007 [22]. Full-scale crash tests featuring New Jersey, F-shape, single slope, and vertical shaped barriers were tabulated and compared. It was found that as the barrier face became more vertical, the vehicle roll and climb decreased. Consequently, the propensity for rollover decreased as the barrier face approached vertical. Tests featuring vertical shaped barriers showed higher impact forces than safety shape or single slope barriers. Nevertheless, the resulting occupant impact velocities and ridedown accelerations were within the NCHRP Report 350 requirements.

Based on previous barrier geometry research, a vertical or near vertical shape is recommended for a new PCB design in order to improve vehicle stability and reduce the propensity of vehicle rollover when impacting a portable barrier. Increased lateral impact loads and decelerations have not been shown to be above current safety limits for rigid, vertical barriers, and the limited deflections allowed by PCB systems will tend to further reduce impact forces and limit occupant risk values.

2.3 Portable Barrier Connections

A literature search was conducted to collect information regarding connection designs employed by portable barrier systems. Several sources were utilized to gather this information, including the Roadside Safety Pooled Fund MASH implementation website [29], FHWA resource charts [30], FHWA eligibility letters [31, 32], crash test reports from various agencies, and a limited patent search.

Various portable barrier connection designs were collected and are summarized in Sections 2.3.1 through 2.3.4. Each connection design was placed in one of four subcategories: pin and loop, cross bolt, interlock, or key and keyway.

2.3.1 Pin and Loop

A total of 99 full-scale crash tests were identified on portable barriers with pin and loop connections. Pin and loop connections connect adjacent segments using a drop pin that passed through loops extending from the ends of adjacent barrier segments. Portable barriers featuring this connection were made of concrete, steel, or plastic, and some featured spring tensioning mechanisms. Examples of each type of pin-and-loop connection-barrier are shown in Sections 2.3.1.1 through 2.3.1.4.

2.3.1.1 Concrete

A total of 29 full-scale crash tests were identified on portable concrete barriers with pin and loop connections. Pin and loop connections in portable concrete barriers typically feature two or three rebar loops extending from each end of the barrier section. A steel pin with a plate welded to the top is dropped into the loops to connect the sections, as shown in Figure 26. This type of connection results in a gap between barrier sections, which acts as a pivot point when the barrier is impacted. The barriers can rotate until the barrier corners lock up and stop the rotation. This rotation leads to higher deflections compared to barriers with a limited gap between the sections or connections with moment continuity.

Figure 26. PCB with Pin and Loop Connection, Test No. 2214TB-2 [6, 33]

One variation of the pin and loop connection for portable concrete barriers features recesses formed into the barrier ends, as shown in Figure 27, which seat a portion of the loops. This reduces the gap between barrier sections to 1 in., which in turn reduces the amount of rotation. When impacted, this barrier locks up sooner than regular pin and loop connected systems and results in lower deflections.

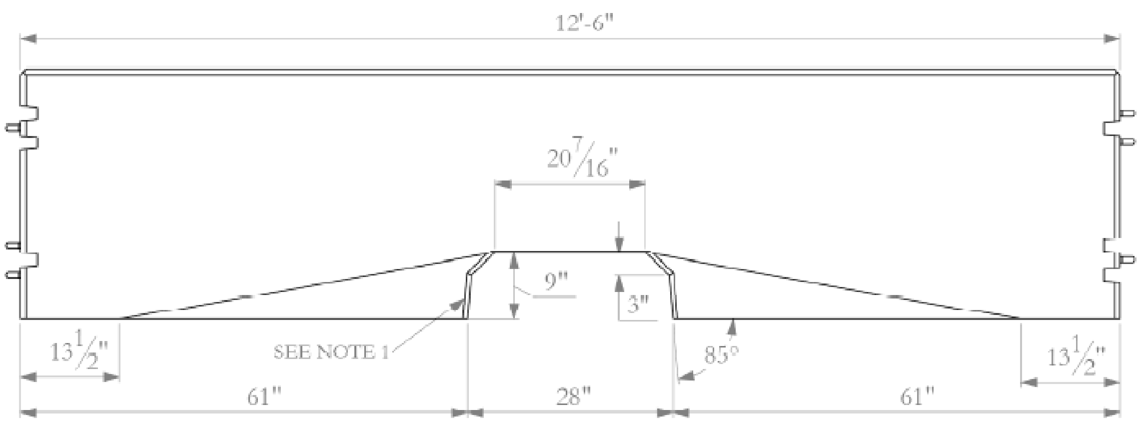
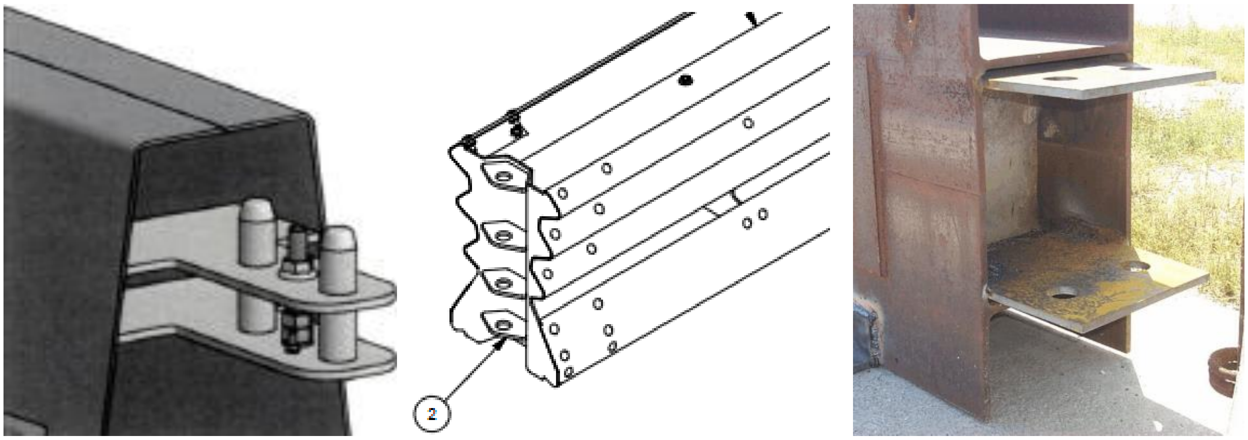


Figure 27. PCB with Pin and Loop Connection and Loop Recesses, Test No. 405160-18-1 [34]

2.3.1.2 Steel

Various portable steel barriers with pin and loop connections exist, most of which are proprietary systems. Full-scale crash tests were identified on 46 systems. Many feature connection plates extending from the barrier ends, which feature embedded pins or holes for pins. Test no. 18760 [35] featured embedded pins and a security bolt, as shown in Figure 28(a). Test no. 01-8430-002 [36] featured a single pin, as shown in Figure 28(b). Test no. HTB-1 [37] featured double pins, shown in Figure 28(c).



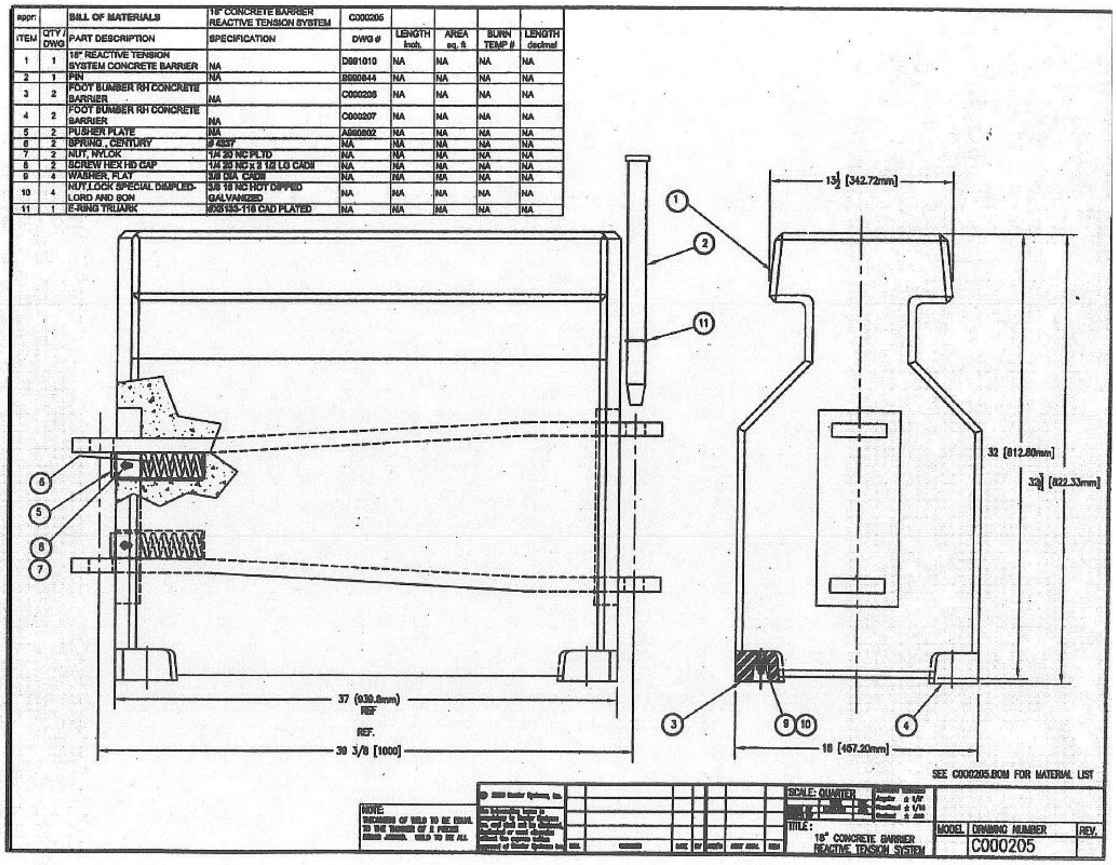
(a) (b) (c)

Figure 28. Portable Steel Barrier with Pin and Loop Connection with (a) Embedded Pins and a Security Bolt, (b) Single Pin, and (c) Double Pins [35-37]

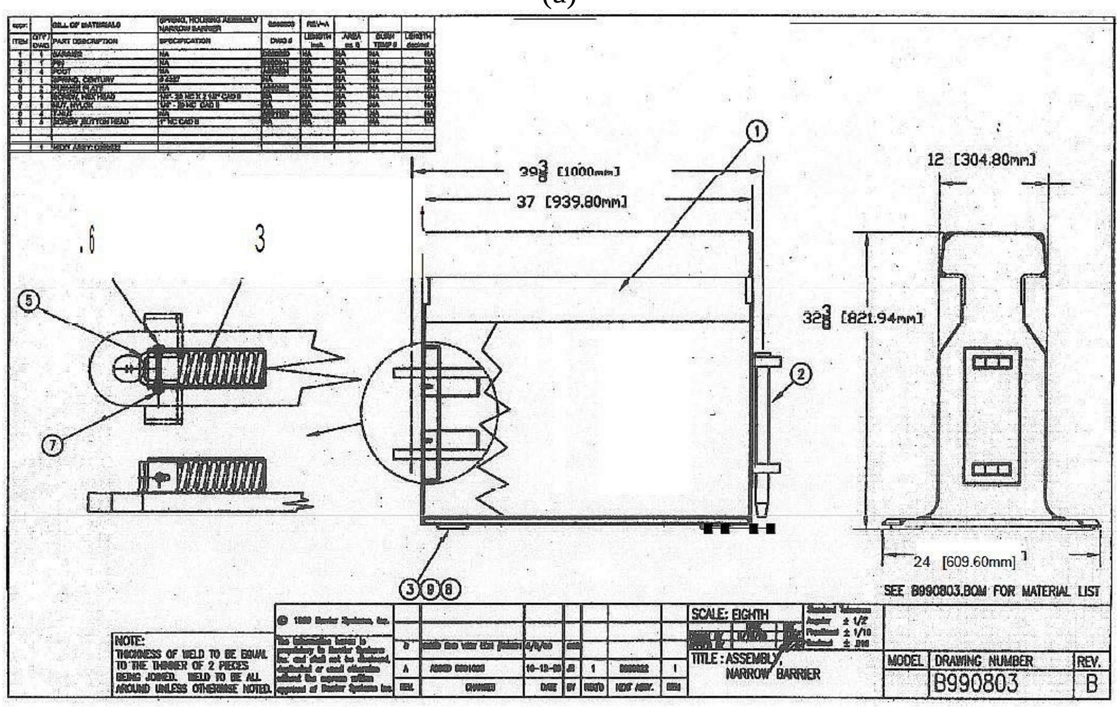
The barrier gap for most of the portable steel barrier tests with pin and loop connections was smaller than that for concrete. Nevertheless, deflections were generally higher due to the steel barriers having less mass than concrete barriers.

2.3.1.3 Concrete and Steel with Springs

Ten full scale crash tests were collected which featured springs or tensioning mechanisms incorporated into the barrier connection. Seven tests featured portable concrete barriers with springs and three featured portable steel barriers with springs, as shown in Figures 29(a) and 29(b), respectively. All full-scale crash tests which featured spring tensioning mechanisms reported lower deflections than comparable systems without springs.



(a)



(b)

Figure 29. Portable Barrier with Pin and Loop Connection and Springs, (a) Concrete and (b) Steel [38]

2.3.1.4 Plastic

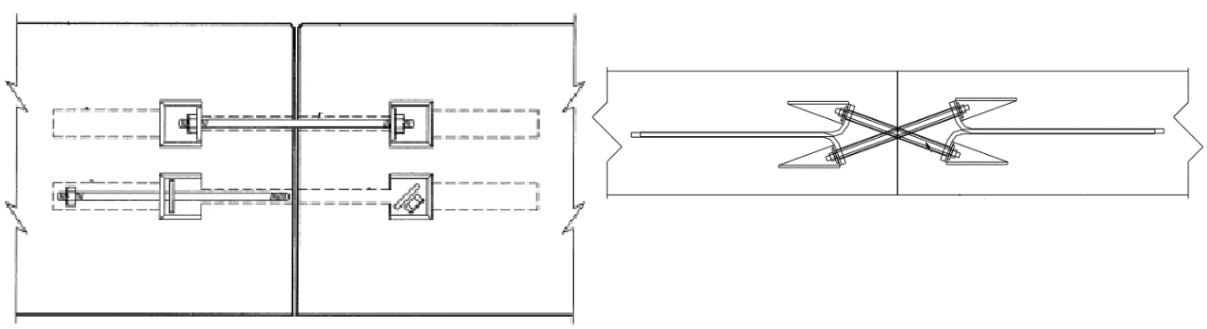
Fourteen full scale crash tests featuring portable plastic barriers with pin and loop connections were collected for this literature review. These barriers feature formed loops on each barrier end, with the number of loops ranging between one and six. An example of one portable plastic barrier with a pin and loop connection, from test no. RLC-2 conducted at MwRSF, features two loops on each barrier end with embedded pins in one end [39]. This barrier is shown in Figure 30.

Figure 30. Portable Plastic Barrier with Pin and Loop Connection, Test No. RLC-2 [39]

Ten out of the fourteen portable plastic barrier tests were conducted at TL-1 or TL-2. Of the four TL-3 tests, one test was conducted according to NCHRP Report 350 test no. 3-10, which resulted in a 5.3-ft deflection [40]. Three tests were performed according to NCHRP Report 350 test no. 3-11. One system was retrofit with cables and had a deflection of 107.9 in. [40]. The other two tests had deflections of 228.4 in. and 271.7 in. [41]. These large deflections were largely due to the lower mass and structural capacity of portable plastic barriers and indicated that this type of barriers may not be capable of meeting the deflection requirements for this project.

2.3.2 Cross Bolt

Ten full scale crash tests were performed on portable concrete barriers with cross bolted connections. Cross bolt connections feature two threaded rods connecting two barrier sections, either straight across or diagonally, as shown in Figures 31(a) and 31(b), respectively. Systems with cross bolt connections result in considerably lower deflections than systems with other types of connections.



(a) (b)

Figure 31. Cross Bolt Connection, Elevation View, (a) Straight, Test No. 400001-BCW1 [42, 43] and (b) Diagonal, Test No. 441623-1 [15]

2.3.3 Interlock

A total of 35 full-scale crash tests were performed on portable barriers with interlock connections. An interlock connection, for this research, was defined as a connection that links together with no required external hardware.

2.3.3.1 Concrete

A proprietary example of an interlock connection for a PCB is the JJ-Hook connection, as shown in Figure 32. Another proprietary interlock connection design is the T-Lok, as shown in Figure 33.

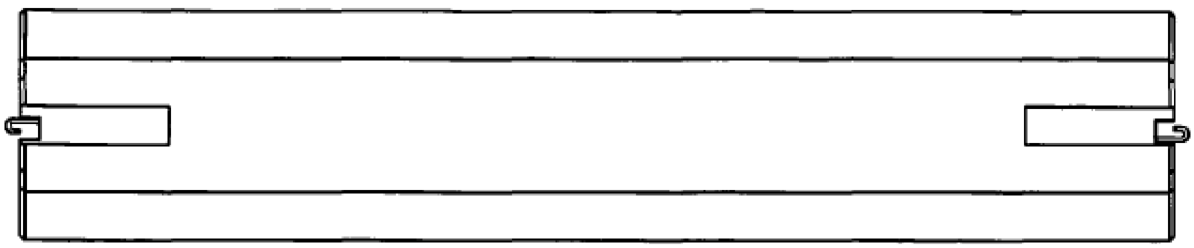


Figure 32. JJ-Hook Connection, Elevation View, Test Nos. 690900-IND2 and 690900-IND3 [44]

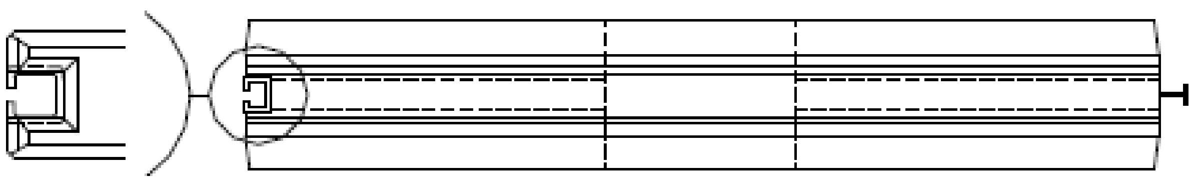


Figure 33. T-Lok Connection, Elevation View, Test No. 400001-RPC4 [45, 46]

2.3.3.2 Steel

The HV2 barrier is a portable steel barrier filled with concrete featuring an interlock connection welded to the barrier ends, as shown in Figure 34. Test no. 690902-SFR6 was performed on the HV2 barrier according to MASH test designation no. 4-11 and resulted in a deflection of 58.0 in. [47].

Figure 34. HV2 Connection, Elevation View, Test Nos. 690902-SFR6, -SFR7, and SFR8 [47]

2.3.3.3 Plastic

A portable plastic barrier with an interlock connection, named the Yodock Barrier, was evaluated to NCHRP Report 350 test no. 3-11 in test no. 400001-YWC6 and resulted in a 168.5-in. deflection [48]. The barrier is shown in Figure 35.

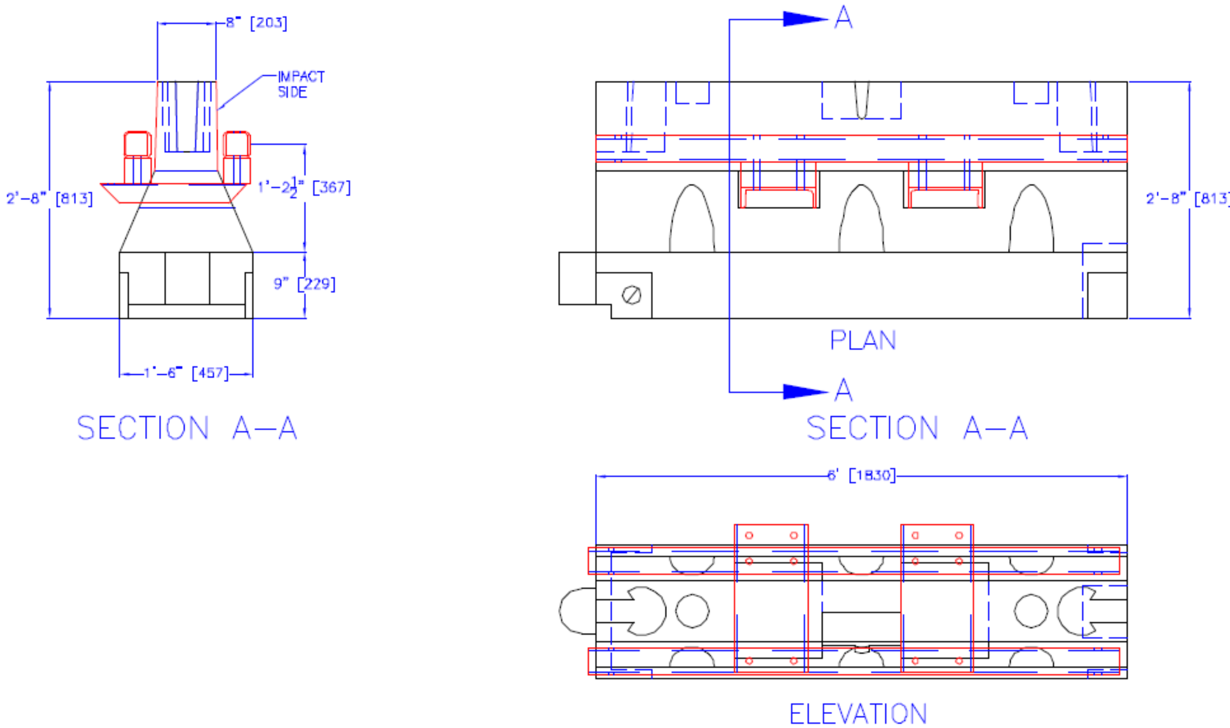


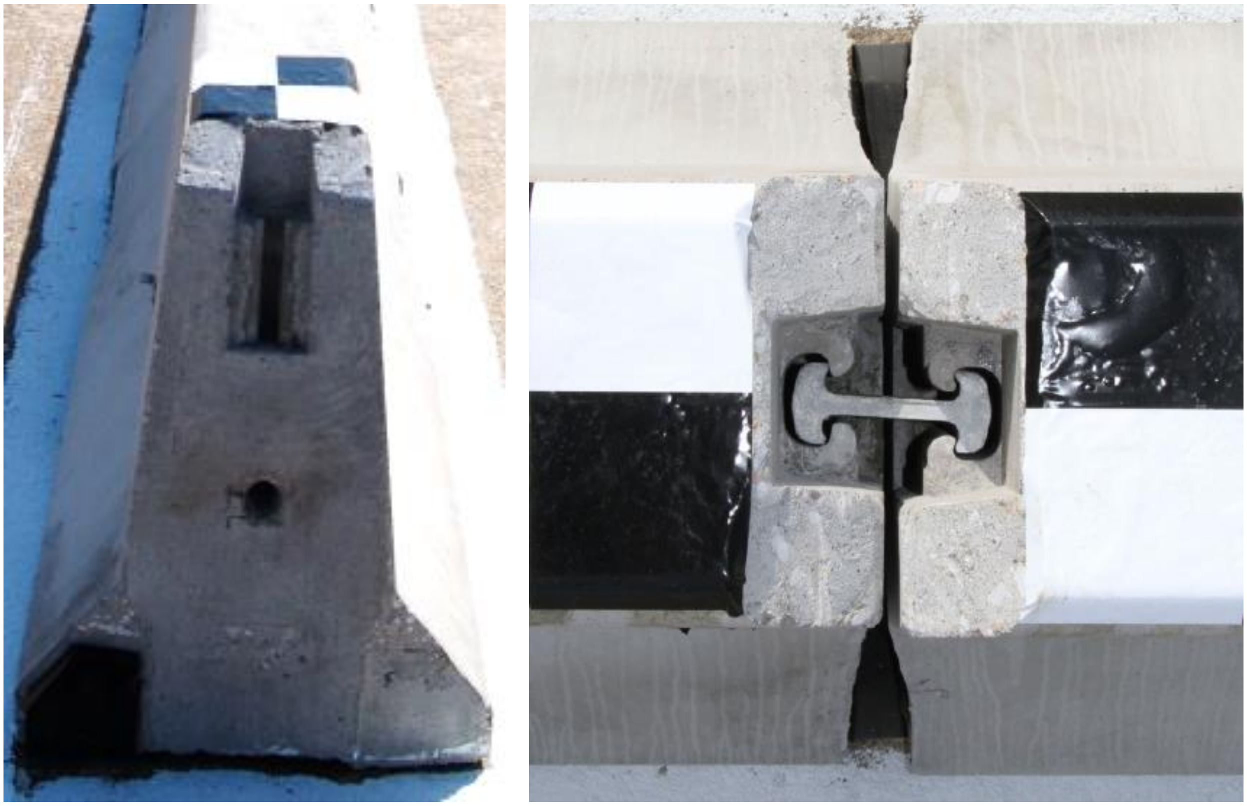
Figure 35. Yodock Barrier, Test Nos. 400001-YWC5, -YWC6, and -YWC8 [48]

2.3.4 Key and Keyway

A total of 23 full-scale crash tests were performed on portable concrete barriers with key and keyway connections. Figure 36 shows an I-section key and keyway connection [49, 50], Figure 37 shows the Delta Block K150 coupling connection [51, 52], and Figure 38 shows a steel bar grid with a U-bar connection [53].

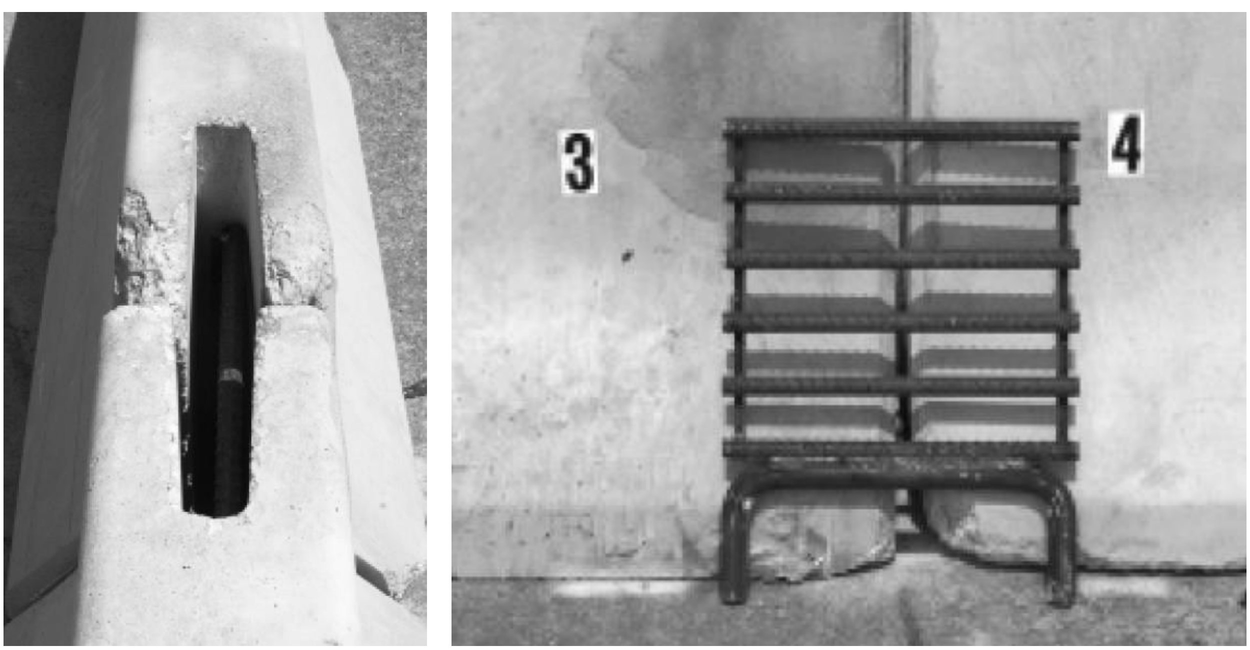
(a) (b)

Figure 36. I-Section Connection, (a) Keyway and (b) Key, Test No. NYTCB-1, NYTCB-2, and NYTCB-3 [49, 50]



(a) (b)

Figure 37. Delta Block K150 Coupling Connection, (a) Keyway and (b) Key, Test Nos. DB-1 and DB-2 [51, 52]



(a) (b)

Figure 38. U-Bar Connection, (a) Keyway and (b) Key, Test No. 441621-2 [53]

2.4 Portable Barrier Full-Scale Crash Tests

A total of 261 full-scale crash tests performed on portable barriers were collected for this literature review and are listed in Tables 5 through 31 and Tables 34 through 42. Each table includes the test number (No.) or barrier name, material (Matl), connection (Conn), shape, anchorage (Anchor), retrofit, test result (Pass/Fail), IS, deflection (Def), height-to-width (HW) ratio, and section length (Length). Portable barriers were crash tested to one of four evaluation criteria: NCHRP Report 230 [13], NCHRP Report 350 [2], and MASH [3] (United States standards) or EN 1317-2 [54] (European standard). Within each evaluation criteria, tests were performed at various test levels, including TL-2, TL-3, TL-4, and TL-5 for the United States standards and T1, T2, T3, N2, H1, H2, H3, H4a, and H4b for the European standards.

If a test featured a concrete barrier, the shape was noted. Otherwise, for steel and plastic systems, shapes vary considerably and were not categorized (NA).

Tested systems utilized one of three anchoring systems: (1) free-standing (None), (2) anchored to pavement at the ends (At Ends), and (3) anchored through all or multiple segments to the pavement (Yes). This information is included in the full-scale crash test tables and is important to consider when comparing deflections. Systems anchored to the pavement or anchored at the ends will have lower deflections compared to similar unanchored systems.

Some systems had a stiffening mechanism added to the top or side of the barrier. These retrofits include side mounted plate, top mounted plate, side mounted tubes, side mounted box beam, top mounted cap, top mounted rail, cables, and tie down straps.

The HW ratio for each portable barrier system was calculated by dividing the height by the largest width (top or bottom). If neither of the heights were not found, the HW ratio was not calculated, and "Not Listed" is reported. Furthermore, if impact severity, deflection, or section length were not found, they were also reported as "Not Listed."

2.4.1 NCHRP Report 230 Full-Scale Crash Tests

NCHRP Report 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* [13], was replaced by NCHRP Report 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* [2], in 1993. Full-scale crash tests performed according to NCHRP Report 230 criteria are listed in the following tables, with test nos. 2-10, 2-11, and 3-11 listed in Tables 5, 6, and 7, respectively.

Table 5. NCHRP Report 230 Test No. 2-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
9901F-2 [55]	Concrete	Cross Bolt	Low Profile	None	None	Pass	16.6	0	0.7	20.0

Table 6. NCHRP Report 230 Test No. 2-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
9901F-1 [55]	Concrete	Cross Bolt	Low Profile	None	None	Pass	57.4	5.0	0.7	20.0

Table 7. NCHRP Report 230 Test No. 3-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
9429K-1 [56]	Concrete	Key and Keyway	Single Slope	None	None	Pass	39.2	6.0	1.8	30.0
9429C-1 [56]	Concrete	Key and Keyway	Single Slope	None	Side Mounted Plate	Pass	37.6	7.0	1.8	30.0

2.4.2 NCHRP Report 350 Full-Scale Crash Tests

Tests performed according to NCHRP Report 350 criteria are listed in the following tables. Tables 8, 9, and 10 show test nos. 1-11, 2-10, and 2-11, respectively. TL-1 is performed at 31.1 mph and TL-2 is performed at 43.5 mph. Test nos. 1-11 and 2-11 are performed with the 2000P pickup truck and test no. 2-10 is performed with the 820C car.

Despite the low impact speeds, the plastic portable barriers exhibited high deflections, even in the presence of retrofitting such as cables and metal plates, making it unlikely plastic portable barriers will meet the low deflection design requirement for this project.

Table 8. NCHRP Report 350 Test No. 1-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
1-11 [57]	Plastic	Pin and Loop	NA	None	None	Pass	24.4	186.2	1.8	5.9

Table 9. NCHRP Report 350 Test No. 2-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Not Listed [58]	Plastic	Pin and Loop	NA	None	None	Pass	Not Listed	Not Listed	1.9	6.6
RLC-2 [39]	Plastic	Pin and Loop	NA	None	None	Pass	16.3	Not Listed	1.7	6.5
2-10 [57]	Plastic	Pin and Loop	NA	None	None	Pass	13.9	71.5	1.8	5.9
147-044 [59]	Plastic	Pin and Loop	NA	None	None	Pass	13.9	39.6	1.5	6.5
Not Listed [60]	Plastic	Pin and Loop	NA	None	Side Mounted Plate	Pass	Not Listed	Not Listed	1.3	6.6

Table 10. NCHRP Report 350 Test No. 2-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
147-043 [59]	Plastic	Pin and Loop	NA	None	None	Pass	52.3	153.6	1.5	6.5
2-11 [40]	Plastic	Pin and Loop	NA	None	Cable	Pass	274.4	70.9	1.8	7.0
Not Listed [60]	Plastic	Pin and Loop	NA	None	Side Mounted Plate	Pass	48.7	157.5	1.3	6.6
400001-YWC5 [48]	Plastic	Interlock	NA	None	Side Mounted Tubes	Pass	45.2	144.9	1.8	6.0
SGL02 [61]	Steel	Pin and Loop	NA	None	None	Pass	49.6	40.6	1.2	26.3

NCHRP Report 350 test no. 3-10 is performed with the 820C small car impacting the barrier at 62 mph at an angle of 20 degrees. Tests performed to these criteria are shown in Table 11.

Table 11. NCHRP Report 350 Test No. 3-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
40001-RPC1 [62]	Concrete	Interlock	F-Shape	None	None	Pass	26.3	7.9	1.4	12.0
552 [63, 64]	Concrete	Pin and Loop	New Jersey	Yes	None	Pass	29.1	1.0	1.3	20.0
RTS02 [38]	Concrete with Springs	Pin and Loop	NA	At Ends	None	Pass	30.5	Not Listed	1.8	3.0
3-10 [40]	Plastic	Pin and Loop	NA	None	Cable	Pass	251.6	64.2	1.8	7.0
400001-YWC8 [48]	Plastic	Interlock	NA	None	Side Mounted Tubes	Pass	25.6	48.4	1.9	6.0
270687-YEW8 [65]	Plastic	Interlock	NA	Yes	Side Mounted Tubes	Pass	Not Listed	Not Listed	1.7	6.0
Not Listed [66]	Steel	Pin and Loop	NA	At Ends	None	Pass	30.9	57.1	1.4	40.0
SGL03 [61]	Steel	Pin and Loop	NA	None	None	Pass	27.9	24.0	1.2	26.3
01-8430-002 [36]	Steel	Pin and Loop	NA	None	None	Pass	29.3	63.0	1.5	13.5
04-0228-001 [67]	Steel Filled with Concrete	Pin and Loop	NA	Yes	None	Pass	33.6	18.3	1.3	3.0
SGB09 [68]	Steel Gate Between Concrete Segments	Pin and Loop	NA	None	None	Pass	30.8	6.3	1.2	26.0

Two tests were found which featured concrete barriers, test nos. 40001-RPC1 [62] and 552 [63, 64]. The unanchored, F-shape, interlock PCB featured in test no. 40001-RPC1 deflected 7.9 in. Three tests were performed with plastic barriers, two of which were unanchored. Test no. 3-10 [40] featured a plastic, pin and loop connected, unanchored portable barrier with cable retrofits, which deflected 64.2 in. Test no. 400001-YWC8 [48] featured a plastic, interlock connected, unanchored portable barrier with side mounted tubes which deflected 48.4 in. under NCHRP Report 350 test no. 3-10 impact conditions.

Two unanchored steel portable barrier systems were evaluated in test nos. SGL03 [61] and 01-8430-002 [36]. Both tests featured steel, pin and loop connected, unanchored, and non-retrofit portable barriers. Test no. SGL03 resulted in a deflection of 24.0 in. and test no. 01-8430-002 resulted in a deflection of 63.0 in. at NCHRP Report 350 test no. 3-10 testing conditions. The barriers evaluated in these two tests featured barrier section lengths of 26.3 ft and 13.5 ft, respectively. Longer barrier section lengths resulted in lower deflections.

NCHRP Report 350 test no. 3-11 is performed with the 2000P pickup truck impacting the barrier at a speed of 62 mph at an angle of 25 degrees. Portable barrier evaluated according to NCHRP Report 350 test no. 3-11 are summarized in Table 12. Comparing tests in Table 12 which feature unanchored and non-retrofit concrete portable barriers, the connection type with the lowest deflection is cross bolt, followed by pin and loop, interlock, and key and keyway. It should be noted that two of the tests featuring key and keyway connections failed. Test no. 441621-2 failed due to vehicle trajectory after impact and test no. 473220-7 failed due to welds in the I-beam connection key failing, which resulted from low weld penetration.

Test nos. QBOR1 [69] and QBD08 [70] feature anchored-at-both-ends, non-retrofit, 3-ft long section length portable concrete barriers with pin and loop connections featuring springs. Reported deflections for these tests were 26.5 in. and 24.1 in., respectively. Test no. 001 [71] features a comparable portable concrete barrier with section lengths of 3.275 ft and no springs in the pin and loop connections, with a deflection of 53.0 in. The pin and loop connection featuring springs resulted in lower deflections.

Unanchored, non-retrofit plastic portable barriers with pin and loop connections were evaluated in two tests (no test numbers were listed), with deflections of 228.35 in. and 271.65 in. [41]. Test no. 3-11 [40] featured a comparable test, which includes a cable retrofit. This portable barrier had a deflection of 107.87 in., significantly lower than plastic portable barrier systems with no retrofit.

Test nos. SGL01 [61] and 01-8430-001 [36] feature unanchored, non-retrofit steel portable barriers with pin and loop connections, and resulted in deflections of 75.6 in. and 157.5 in., respectively. The system tested in test no. SGL01 had a section length of 26.25 ft and test no. 01-8430-001 had a section length of 13.5 ft. The system with longer section lengths, test no. SGL01, resulted in lower deflections.

Furthermore, test nos. SGL01 and 01-8430-001 resulted in higher deflections than comparable portable concrete barrier systems, unanchored and non-retrofit PCB systems. Two exceptions, test nos. 441621-1 and 441621-2 [53], resulted in deflections greater than was seen in test no. SGL01.

Table 12. NCHRP Report 350 Test No. 3-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
001 [71]	Concrete	Pin and Loop	NA	At Ends	None	Pass	104.8	53.0	1.3	3.3
446924-1 [16]	Concrete	Cross Bolt	F-Shape	None	None	Pass	109.7	27.0	1.4	10.0
452106-4 [72]	Concrete	Cross Bolt	F-Shape	None	None	Pass	123.0	13.8	1.3	30.0
441623-1 [15]	Concrete	Cross Bolt	F-Shape	None	None	Pass	110.7	19.0	1.4	30.0
40001-RPC3 [62]	Concrete	Interlock	F-Shape	None	None	Pass	111.1	48.8	1.4	12.0
400001-ESI1 [73]	Concrete	Interlock	New Jersey	None	None	Pass	103.8	51.2	1.3	12.0
441621-1 [53]	Concrete	Key and Keyway	New Jersey	None	None	Pass	105.7	107.9	Not Listed	30.0
441621-2 [53]	Concrete	Key and Keyway	New Jersey	None	None	Fail	102.5	148.8	Not Listed	30.0
473220-7 [74]	Concrete	Key and Keyway	New Jersey	None	None	Fail	107.3	Not Listed	Not Listed	20.0
402041-1 [75, 76]	Concrete	Pin and Loop	F-Shape	None	None	Pass	99.8	72.0	1.3	20.0
KAR21007-01 [77, 78]	Concrete	Pin and Loop	F-Shape	None	None	Pass	105.3	30.0	1.3	12.5
KAR21007-02 [77, 78]	Concrete	Pin and Loop	F-Shape	None	None	Pass	107.8	32.0	1.6	12.5
ITMP-1 [4]	Concrete	Pin and Loop	F-Shape	None	None	Fail	130.0	39.0	1.4	12.5
ITMP-2 [4]	Concrete	Pin and Loop	F-Shape	None	None	Pass	119.0	45.3	1.4	12.5
011012 [79, 80]	Concrete	Pin and Loop	New Jersey	None	None	Pass	Not Listed	65.8	1.3	10.0
441621-3 [53]	Concrete	Key and Keyway	New Jersey	None	Side Mounted Plate	Fail	108.5	43.3	Not Listed	30.0

Table 13. NCHRP Report 350 Test No. 3-11 (Cont.)

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
405160-3-2a [81]	Concrete	Pin and Loop	F-Shape	Yes	None	Pass	113.0	11.5	1.3	12.5
FTB-1 [82]	Concrete	Pin and Loop	F-Shape	Yes	None	Pass	102.5	21.8	1.4	12.5
551 [63, 64]	Concrete	Pin and Loop	New Jersey	Yes	None	Pass	103.7	10.3	1.3	20.0
405160-3-1 [81]	Concrete	Pin and Loop	New Jersey	Yes	None	Fail	115.5	0	1.3	12.5
ITD-1 [83]	Concrete	Pin and Loop	F-Shape	Yes	Tie Down Straps Through Pin Connection	Pass	92.2	37.8	1.4	12.5
KTB-1	Concrete	Pin and Loop	F-Shape	Yes	None	Pass	104.4	11.3	1.4	12.5
RTS01 [38]	Concrete with Springs	Pin and Loop	NA	At Ends	None	Pass	99.6	Not Listed	1.8	3.0
RTS03 [38]	Concrete with Springs	Pin and Loop	NA	At Ends	None	Pass	99.6	Not Listed	1.8	3.0
QBOR1 [69]	Concrete with Springs	Pin and Loop	NA	At Ends	None	Pass	104.4	26.5	1.8	3.0
QBD08 [70]	Concrete with Springs	Pin and Loop	NA	At Ends	None	Pass	94.1	24.1	1.8	3.0
Not Listed [41]	Plastic	Pin and Loop	NA	None	None	Pass	Not Listed	228.4	1.5	6.5
Not Listed [41]	Plastic	Pin and Loop	NA	None	None	Pass	Not Listed	271.7	1.5	6.5
3-11 [40]	Plastic	Pin and Loop	NA	None	Cable	Pass	636.1	107.9	1.8	7.0
400001-YWC6 [48]	Plastic	Interlock	NA	None	Side Mounted Tubes	Pass	98.8	168.5	1.9	6.0
270687-YEW7 [65]	Plastic	Interlock	NA	Yes	Side Mounted Tubes	Pass	Not Listed	Not Listed	1.7	6.0
ZG-USA-4 [84]	Steel	Interlock	NA	At Ends	None	Pass	110.4	72.0	1.2	50.0
Not Listed [85]	Steel	Interlock	NA	At Ends	None	Pass	109.1	38.2	1.2	13.1
Not Listed [66]	Steel	Pin and Loop	NA	At Ends	None	Pass	105.5	72.8	1.4	40.0
ORB01 [66]	Steel	Pin and Loop	NA	At Ends	None	Pass	103.8	37.4	1.4	40.0
55-8430-003 [36]	Steel	Pin and Loop	NA	At Ends	None	Pass	103.0	82.8	1.5	13.5
SGL01 [61]	Steel	Pin and Loop	NA	None	None	Pass	104.1	75.6	1.2	26.3
01-8430-001 [36]	Steel	Pin and Loop	NA	None	None	Pass	107.2	157.5	1.5	13.5
ZG-USA-2 [84]	Steel	Interlock	NA	Yes	None	Pass	99.8	12.0	1.2	50.0
HTB-1 [37]	Steel	Pin and Loop	NA	Yes	None	Fail	116.9	2.5	Not Listed	20.0
HTB-2 [37]	Steel	Pin and Loop	NA	Yes	None	Pass	110.3	12.4	Not Listed	20.0
01-8430-005 [86]	Steel	Pin and Loop	NA	Yes	None	Pass	104.6	11.8	1.5	38.6
BG808 [87]	Steel	Pin and Loop	NA	Yes	Top Mounted Plate	Pass	105.7	12.0	1.5	39.4
04-0228-002 [67]	Steel Filled with Concrete	Pin and Loop	NA	Yes	None	Pass	96.4	34.5	1.3	3.0
SGB07 [68]	Steel Gate Between Concrete Segments	Pin and Loop	NA	None	None	Pass	100.9	18.9	1.2	26.0
RTS04 [38]	Steel with Springs	Pin and Loop	NA	At Ends	None	Pass	99.6	Not Listed	1.3	3.0

NCHRP Report 350 test no. 3-21 evaluates a barrier transition impacted by the 2000P pickup truck at 62 mph and 25 degrees. Full-scale crash tests of portable barriers performed according to NCHRP Report 350 test no. 3-21 criteria are shown in Table 14.

Table 14. NCHRP Report 350 Test No. 3-21

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
BG801 [88]	Steel	Pin and Loop	NA	At Ends	None	Pass	102.9	39.4	1.5	39.3
BG807 [89]	Steel	Pin and Loop	NA	At Ends	None	Pass	99.3	45.7	1.5	20.0
102350.02-5-10 [66]	Steel	Pin and Loop	NA	At Ends	None	Pass	99.6	38.2	1.4	40.0
01-8430-004 [90]	Steel	Pin and Loop	NA	At Ends	None	Pass	100.4	27.6	1.5	6.7
01-8430-010 [91]	Steel	Pin and Loop	NA	At Ends	None	Pass	104.1	43.3	1.5	Not Listed
WGB03 [92]	Steel	Pin and Loop	NA	None	None	Pass	101.1	105.0	1.2	28.0
WGB04 [92]	Steel	Pin and Loop	NA	None	None	Pass	106.2	49.0	1.2	28.0
AG8M1 [92]	Steel	Pin and Loop	NA	None	None	Pass	104.7	28.0	1.2	28.0
SGL04 [61]	Steel Gate Between Concrete	Pin and Loop	NA	None	None	Pass	102.5	61.8	1.2	26.3
01-8430-006 [93]	Steel Gate Between Concrete	Pin and Loop	NA	At Ends	None	Pass	100.8	15.8	1.5	Not Listed
SGB11 [68]	Steel Gate Between Concrete	Pin and Loop	NA	None	None	Pass	95.9	13.0	1.2	26.0
SGB06 [68]	Steel Gate Between Concrete	Pin and Loop	NA	None	None	Pass	97.8	22.4	1.2	26.0

Test no. 4-10 under NCHRP Report 350 criteria features the 820C small car impacting the system at 20 degrees and 62.1 mph. One test was performed to these criteria and is shown in 15.

Table 15. NCHRP Report 350 Test No. 4-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
TB11 [94]	Steel	Pin and Loop	NA	At Ends	None	Pass	29.9	43.3	1.5	38.6

Tests performed according to NCHRP Report 350 test no. 4-12 are shown in Table 16. This test features the 8000S single-unit truck impacting the system at 50 mph and 15 degrees. Test no. KAR21007-03 [77, 78] featured a pin and loop connected, F-shape, unanchored, non-retrofit PCB which resulted in a deflection of 32.5 in. Two tests featured steel portable barriers anchored at the ends with no retrofit. Test no. ZG-USA-6 [84] featured an interlock connection and a 50-ft section length and resulted in a deflection of 57.0 in. Test no. TB51 [94] featured a pin and loop connection and a 38.6-ft section length and resulted in a deflection of 94.4 in.

Table 16. NCHRP Report 350 Test No. 4-12

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
KAR21007-03 [77, 78]	Concrete	Pin and Loop	F-Shape	None	None	Pass	87.4	32.5	1.6	12.5
ZG-USA-6 [84]	Steel	Interlock	NA	At Ends	None	Pass	95.6	57.0	1.2	50.0
TB51 [94]	Steel	Pin and Loop	NA	At Ends	None	Pass	212.1	94.4	1.5	38.6

2.4.3 MASH Full-Scale Crash Tests

NCHRP Report 350 was replaced in 2009 by MASH [1, 3], which is published by AASHTO. Full-scale crash tests performed on portable barriers according to MASH criteria are shown in Tables 17 through 31.

Tables 17 through 20 show MASH TL-2 full-scale crash tests. Test nos. 2-10 and 2-20, as shown in Tables 17 and 19, respectively, were performed with the 1100C passenger car impacting the system at 44 mph and 25 degrees. Test nos. 2-11 and 2-21, as shown in Tables 18 and 20, respectively, were performed with the 2270P pickup truck impacting the barrier at a speed of 44 mph and an angle of 25 degrees. Test nos. 2-10 and 2-11 evaluate length-of-need (LON) systems and test nos. 2-20 and 2-21 evaluate transition systems.

Table 17. MASH Test No. 2-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
131393.2-10 [95]	Steel	Pin and Loop	NA	None	None	Pass	25.9	29.1	1.2	13.0

Table 18. MASH Test No. 2-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Not Listed [58]	Plastic	Pin and Loop	NA	None	None	Pass	Not Listed	Not Listed	1.9	6.6
131393.2-11 [95]	Steel	Pin and Loop	NA	None	None	Pass	55.7	47.2	1.2	13.0

Table 19. MASH Test No. 2-20

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
131393.2-20 [95]	Steel	Pin and Loop	NA	None	None	Pass	27.9	47.2	1.2	13.0

Table 20. MASH Test No. 2-21

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
131393.2-21 [95]	Steel	Pin and Loop	NA	None	None	Pass	60.8	110.2	1.2	13.0

MASH test designation no. 3-10 is performed with the 1100C car impacting the barrier system at a speed of 62 mph and an angle of 25 degrees. Tests performed to these criteria are shown in Table 21. When comparing unanchored non-retrofit portable concrete barriers, the type of connection resulting in the lowest to highest barrier deflections were the cross bolt, key and keyway, interlock, and pin and loop, respectively. It should be noted that the test featuring the cross-bolt connection, test no. 469688-1-1 [14], had considerably longer section lengths than the other PCB tests.

Test no. 690900-LTS1 [96] featured a pin and loop connected, unanchored, non-retrofit PCB with springs and section lengths of 3 ft and resulted in a deflection of 26.0 in. Test no. 607911-1 [97] featured a pin and loop connected, unanchored, non-retrofit portable concrete barrier with section lengths of 12.5 ft which resulted in a deflection of 36.2 in. The barrier evaluated in test no. 690900-LTS1, which incorporated springs, resulted in a lower deflection despite having a shorter barrier length.

Test no. 131393.3-10FS [98] featured an unanchored, non-retrofit steel portable barrier with a pin and loop connection. The steel configuration resulted in a higher deflection than a comparable concrete test, test no. 607911-1 [97].

Table 21. MASH Test No. 3-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
469688-1-1 [14]	Concrete	Cross Bolt	Low Profile	None	None	Pass	62.0	13.2	1.0	30.0
690900-JJH11 [99]	Concrete	Interlock	F-Shape	None	None	Pass	55.0	26.2	1.3	12.0
135780.3-10 [100]	Concrete	Interlock	F-Shape	None	None	Pass	53.7	32.3	1.3	19.7
DB-1 [51, 52]	Concrete	Key and Keyway	F-Shape	None	None	Pass	60.6	22.3	1.4	12.5
607911-1 [97]	Concrete	Pin and Loop	F-Shape	None	None	Pass	58.0	36.2	1.3	12.5
690900-LTS1 [96]	Concrete with Springs	Pin and Loop	NA	None	None	Pass	58.0	26.0	1.8	3.0
690900-LTS5 [101]	Concrete with Springs	Pin and Loop	NA	None	None	Pass	77.0	27.6	1.8	3.3
18760 [35]	Steel	Pin and Loop	NA	At Ends	None	Pass	56.2	64.5	1.5	19.7
131393.3-10FS [98]	Steel	Pin and Loop	NA	None	None	Pass	56.5	43.2	1.2	13.0
ZG-USA-1 [84, 102]	Steel	Interlock	NA	Yes	None	Pass	52.3	8.0	1.2	50.0
18829 [103]	Steel	Pin and Loop	NA	Yes	None	Pass	56.9	1.4	1.7	19.7
18648 [104]	Steel	Pin and Loop	NA	Yes	None	Pass	59.4	13.8	1.8	19.0
690900-HSI8 [105]	Steel	Interlock	NA	Yes	None	Pass	57.0	9.7	1.1	50.0
131393.3-10LDS [106]	Steel	Interlock	NA	Yes	None	Pass	57.2	22.0	1.2	13.0
690900-LTS3 [107]	Steel Filled with Concrete and Springs	Pin and Loop	NA	None	None	Pass	55.0	27.6	1.4	3.3

Full-scale MASH tests performed according to test designation no. 3-11 criteria are listed in Table 22. In test designation no. 3-11, a 2270P pickup truck impacts the system at 62 mph and 25 degrees. For unanchored, non-retrofit concrete barriers, the connection with the lowest deflection was the cross bolt, followed by key and keyway, interlock, and pin and loop. It should be noted the systems with cross bolt connections feature 30-ft long sections, considerably larger than the section lengths for the other types of connections. Test no. 405160-18-1 [34], featuring a single slope barrier design, failed due to vehicle rollover and subsequent occupant compartment deformation.

Three tests featured an unanchored, retrofit PCBs connected by pins and loops. The retrofits include a side mounted plate or side mounted box beam. Compared to non-retrofit configurations, the retrofit configurations generally had lower deflections. However, the deflections for unanchored, retrofit PCB systems were still larger than those for unanchored, non-retrofit PCBs with cross bolt connections.

Twenty-one tests featured anchored PCBs with no retrofits and three were determined to fail evaluation criteria. Test no. NJPCB-8 [108] failed due to occupant compartment deformation and test nos. NJPCB-9 [109] and 607911-3 [110] failed due to vehicle rollover.

Test no. 131393.3-11FS [98] featured unanchored, non-retrofit steel portable barriers connected by pins and loops. Compared to similar concrete portable barriers, the steel had a generally higher deflection.

Three non-retrofit steel portable barriers with end anchors were tested, two featuring interlock connections and one featuring a pin and loop connection. Test nos. 690900-HIS2 [111] and ZG-USA-5 [102], which featured interlock connections and section lengths of 50-ft, resulted in deflections of 77.4 in. and 76.0 in., respectively. The pin and loop system with 19.7-ft section lengths, evaluated in test no. 18761 [35], resulted in a deflection of 66.5 in.

Table 22. MASH Test No. 3-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
NYTCB-2 [49]	Concrete	Key and Keyway	New Jersey	At Ends	None	Pass	119.2	40.3	1.3	20.0
NYTCB-1 [49, 50]	Concrete	Key and Keyway	New Jersey	At Ends	Side Mounted Box Beam	Pass	111.0	27.6	1.3	20.0
NYTCB-3 [49]	Concrete	Key and Keyway	New Jersey	At Ends	Side Mounted Box Beam	Pass	115.0	30.9	1.3	20.0
400001-BCW1 [42, 43]	Concrete	Cross Bolt	F-Shape	None	None	Pass	106.5	31.0	1.3	30.0
469688-1-2 [14]	Concrete	Cross Bolt	Low Profile	None	None	Pass	111.6	25.0	1.0	30.0
400001-RPC4 [45, 46]	Concrete	Interlock	F-Shape	None	None	Pass	120.9	50.0	1.4	12.0
690900-JJH10 [99]	Concrete	Interlock	F-Shape	None	None	Pass	124.0	64.2	1.3	12.0
135780.3-11 [100]	Concrete	Interlock	F-Shape	None	None	Pass	111.9	62.9	1.3	19.7
DB-2 [51, 52]	Concrete	Key and Keyway	F-Shape	None	None	Pass	125.4	56.8	1.4	12.5
607911-2 [97]	Concrete	Pin and Loop	F-Shape	None	None	Pass	118.0	63.4	1.3	12.5
2214TB-2 [6, 33]	Concrete	Pin and Loop	F-Shape	None	None	Pass	117.8	79.6	1.4	12.5
2214TB-1 [5]	Concrete	Pin and Loop	F-Shape	None	None	Pass	120.4	56.7	1.4	12.5
PCMB-1 [112]	Concrete	Pin and Loop	F-Shape	None	None	Pass	122.6	84.6	1.4	12.5
405160-18-1 [34]	Concrete	Pin and Loop	Single Slope	None	None	Fail	116.9	58.8	1.6	12.5
Not Listed [9]	Concrete	Pin and Loop	F-Shape	None	Side Mounted Plate	Pass	Not Listed	59.0	Not Listed	10.0
RDTCB-2 [113, 114]	Concrete	Pin and Loop	F-Shape	None	Top Mounted Cap and Side Mounted Box Beam	Pass	128.6	40.7	1.4	12.5
RDTCB-1 [113, 115]	Concrete	Pin and Loop	F-Shape	None	Top Mounted Cap and Side Mounted Box Beam	Pass	119.8	43.0	1.4	12.5
510602-JJH8 [116, 117]	Concrete	Interlock	F-Shape	Yes	None	Pass	114.5	8.8	1.4	12.5
510602-JJH9 [118, 119]	Concrete	Interlock	F-Shape	Yes	None	Pass	114.5	5.9	1.4	12.5
469467-5-1 [120]	Concrete	Interlock	F-Shape	Yes	None	Pass	176.0	24.6	1.3	30.0
NYTCB-4 [121]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	109.9	64.8	1.3	20.0

Table 23. MASH Test No. 3-11 (Cont.)

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
NYTCB-5 [122]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	133.4	20.5	1.3	20.0
NJPCB-1 [123]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	114.9	13.5	1.3	20.0
NJPCB-2 [26]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	112.6	4.9	1.3	20.0
NJPCB-3 [124]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	122.9	38.1	1.3	20.0
NJPCB-4 [125]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	113.4	40.7	1.3	20.0
NJPCB-6 [126]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	119.0	15.2	1.3	20.0
NJPCB-7 [127]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	119.5	11.4	1.3	20.0
2011_11 [128]	Concrete	Key and Keyway	New Jersey	Yes	None	Pass	102.7	0.5	0.0	19.7
NJPCB-8 [108]	Concrete	Key and Keyway	New Jersey	Yes	None	Fail	118.6	3.8	1.3	20.0
NJPCB-9 [109]	Concrete	Key and Keyway	New Jersey	Yes	None	Fail	188.5	14.6	1.3	20.0
607911-3 [110]	Concrete	Pin and Loop	F-Shape	Yes	None	Fail	128.0	31.4	1.3	12.5
Not Listed [9]	Concrete	Pin and Loop	F-Shape	Yes	None	Pass	Not Listed	22.1	Not Listed	12.5
405160-25-1 [129]	Concrete	Pin and Loop	F-Shape	Yes	None	Pass	115.0	17.8	1.3	12.5
NJPCB-5 [130]	Concrete	Key and Keyway	New Jersey	Yes	Side Mounted Box Beam	Pass	116.3	33.0	1.3	20.0
690900-SBK1 [131]	Concrete	Interlock	F-Shape	Yes	Side Mounted Plate	Pass	117.7	18.9	Not Listed	Not Listed
690900-IND2 [44]	Concrete	Interlock	F-Shape	Yes	Top Mounted Plate	Pass	121.1	11.9	1.3	10.0
690900-IND3 [44]	Concrete	Interlock	F-Shape	Yes	Top Mounted Plate	Pass	126.9	13.3	1.3	10.0
690900-LTS2 [96]	Concrete with Springs	Pin and Loop	NA	None	None	Pass	119.0	41.4	1.8	3.0
690900-LTS6 [101]	Concrete with Springs	Pin and Loop	NA	None	None	Pass	114.0	47.0	1.8	3.3
690900-HSI2 [111]	Steel	Interlock	NA	At Ends	None	Pass	119.0	81.4	Not Listed	50.0
ZG-USA-5 [102]	Steel	Interlock	NA	At Ends	None	Pass	108.0	76.0	1.2	50.0
690900-HSI5 [105]	Steel	Interlock	NA	Yes	None	Pass	136.0	23.4	1.1	50.0
18761 [35]	Steel	Pin and Loop	NA	At Ends	None	Pass	122.1	66.5	1.5	19.7
131393.3-11FS [98]	Steel	Pin and Loop	NA	None	None	Pass	106.8	74.4	1.2	13.0
690900-HSI1 [132]	Steel	Interlock	NA	Yes	None	Pass	127.0	38.9	Not Listed	Not Listed
ZG-USA-3 [102]	Steel	Interlock	NA	Yes	None	Pass	119.2	16.0	1.2	50.0
BG1615 [103]	Steel	Pin and Loop	NA	Yes	None	Pass	113.3	18.5	1.7	39.4
18664 [104]	Steel	Pin and Loop	NA	Yes	None	Pass	125.1	25.2	1.8	19.0
131393.3-11LDS [106]	Steel	Interlock	NA	Yes	None	Pass	117.8	34.6	1.2	13.0
690900-LTS4 [107]	Steel Filled with Concrete and Springs	Pin and Loop	NA	None	None	Pass	117.0	47.6	1.4	3.3

Testing according to MASH test designation no. 3-21, for evaluation of a transition system, requires a 2270P pickup truck to impact a barrier at a speed of 62 mph at an angle of 25 degrees. Full-scale crash tests performed at MASH test designation no. 3-21 are shown in Table 24.

Table 24. MASH Test No. 3-21

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
601651-1 [133]	Concrete	Pin and Loop	F-Shape	Yes	None	Pass	120.7	34.2	1.3	12.5
NPD321-C1 [134]	Concrete with Springs	Pin and Loop	NA	Yes	None	Pass	116.4	42.1	1.3	3.9
TCBT-1	Concrete	Pin and Loop	F-Shape	Yes	Thrie Beam and Cap	Pass	114.1	2.6	1.42	12.5
TCBT-2		Pin and Loop	F-Shape	Yes	Thrie Beam and Cap	Pass	125.8	44.3	1.42	12.5

One test performed according to MASH test designation no. 3-35, for evaluating terminals and redirective crash cushions, is shown in Table 25. MASH test designation no. 3-35 is performed with a 2270P pickup truck impacting the system at 62 mph and 25 degrees.

Table 25. MASH Test No. 3-35

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
NELON-1 [135]	Concrete	Pin and Loop	F-Shape	None	None	Pass	113.6	128.3	1.4	12.5

One full-scale crash test performed according to MASH test designation no. 3-37, which evaluates terminals and redirective crash cushions, is shown in Table 26. MASH test designation no. 3-37 requires an impact speed of 62 mph and an impact angle of 25 degrees with a 2270P pickup truck.

Table 26. MASH Test No. 3-37

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
NELON-2 [135]	Concrete	Pin and Loop	F-Shape	None	None	Fail	113.8	127.8	1.4	12.5

MASH test no. designation 4-10 is performed with an 1100C car impacting a barrier at a speed of 62 mph and an angle of 25 degrees. Tests performed according to this evaluation criteria are shown in Table 27.

Table 27. MASH Test No. 4-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
18648 [136]	Steel	Pin and Loop	NA	Yes	None	Pass	59.4	13.8	1.8	19.0
BASt/2004-7D-33/HB [137]	Steel	Interlock	NA	Yes	Top Rail	Pass	Not Listed	Not Listed	2.5	20.0
131393-4.10HC [138]	Steel	Interlock	NA	Yes	None	Pass	55.6	70.9	1.2	13.0
690902-SFR7 [47]	Steel Filled with Concrete	Interlock	NA	None	None	Pass	53.0	29.4	2.0	19.0

Tests performed according to MASH test designation no. 4-11 are shown in Table 28. This evaluation criteria requires a 2270P pickup truck to impact a barrier at 62 mph and 25 degrees.

Table 28. MASH Test Designation No. 4-11

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
18664 [136]	Steel	Pin and Loop	NA	Yes	None	Pass	125.1	25.2	1.8	19.0
131393.4-11HC [138]	Steel	Interlock	NA	Yes	None	Pass	114.0	90.6	1.2	13.0
690902-SFR6 [47]	Steel Filled with Concrete	Interlock	NA	None	None	Pass	106.0	58.0	2.0	19.0

MASH test designation no. 4-12 is performed with a 10000S single-unit truck impacting a system at a speed of 56 mph and an angle of 15 degrees. Tests performed according to MASH test designation no. 4-12 are shown in Table 29. An unanchored, non-retrofit concrete portable barrier with a cross bolt connection was tested to MASH test designation no. 4-12, which resulted in a deflection of 33.0 in. [1].

Table 29. MASH Test No. 4-12

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Not Listed [9]	Concrete	Cross Bolt	Single Slope	None	None	Pass	Not Listed	33.0	Not Listed	30.0
490027-2-1 [139]	Concrete	Cross Bolt	Single Slope	Yes	None	Pass	184.0	7.1	1.8	30.0
18650 [136]	Steel	Pin and Loop	NA	Yes	None	Pass	151.9	81.5	1.8	19.0
BASt/2004-7D-34/HB [137]	Steel	Interlock	NA	Yes	Top Rail	Pass	Not Listed	Not Listed	2.5	20.0
131393.4-12HC [138]	Steel	Interlock	NA	Yes	None	Pass	153.7	97.2	1.2	13.0
690902-SFR8 [47]	Steel Filled with Concrete	Interlock	NA	None	None	Pass	167.0	93.2	2.0	19.0

Test designation no. 5-10 is performed with an 1100C car impacting a barrier at 62 mph at an angle of 25 degrees, according to MASH evaluation criteria. One test performed at this evaluation criteria is shown in Table 30.

Table 30. MASH Test No. 5-10

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
BASt/2006-7D-03/HK [137]	Steel	Interlock	NA	Yes	Top Rail	Pass	Not Listed	Not Listed	3.3	20.0

One test performed according to MASH test designation no. 5-12 evaluation criteria is shown in Table 31. MASH test designation no. 5-12 is performed with the 36000V tractor-van trailer impacting a system at a speed of 50 mph at an angle of 15 degrees.

Table 31. MASH Test No. 5-12

Test No.	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
BASt/2006-7D-04/HK [137]	Steel	Interlock	NA	Yes	Top Rail	Pass	Not Listed	Not Listed	3.3	20.0

2.4.4 EN 1317-2 Full-Scale Crash Tests

Portable barriers evaluated to EN 1317-2 criteria [54], the European standard evaluation criteria, were found for this research and are shown in Tables 34 through 42. Tests and test conditions are shown in Table 32 and corresponding containment levels are shown in Table 33. Compared to MASH, test conditions for EN 1317-2 feature slower impact speeds, lower impact angles, and lighter vehicles. Test vehicles include cars, rigid heavy good vehicles (HGVs), buses, and articulated HGVs.

Table 32. EN 1317-2 Test Conditions [54]

Test	Impact Speed (mph)	Impact Angle (deg.)	Vehicle Type	Vehicle Mass (lb)
TB 11	62.1	20	Car	1,984
TB 21	49.7	8	Car	2,866
TB 22	49.7	15	Car	2,866
TB 31	49.7	20	Car	3,307
TB 32	68.4	20	Car	3,307
TB 41	43.5	8	Rigid HGV	22,046
TB 42	43.5	15	Rigid HGV	22,046
TB 51	43.5	20	Bus	28,660
TB 61	49.7	20	Rigid HGV	35,274
TB 71	40.4	20	Rigid HGV	66,139
TB 81	40.4	20	Articulated HGV	83,776

Table 33. EN 1317-2 Containment Levels and Tests [54]

Containment Level		**Test No.**
Low Angle Containment	T1	TB 21
	T2	TB 22
	T3	TB 21 TB 41
Normal Containment	N1	TB 31
	N2	TB 11 TB 32
Higher Containment	H1	TB 11 TB 42
	L1	TB 11 TB 32 TB 42
	H2	TB 11 TB 51
	L2	TB 11 TB 32 TB 51
	H3	TB 11 TB 61
	L3	TB 11 TB 32 TB 61
Very High Containment	H4a	TB 11 TB 71
	H4b	TB 11 TB 81
	L4a	TB 11 TB 32 TB 71
	L4b	TB 11 TB 32 TB 81

Portable barriers evaluated to low angle containment levels T1, T2, and T3 are listed in Tables 34, 35, and 36, respectively. Within the normal containment level, only barriers evaluated to N2 criteria were found, as shown in Table 37. Table nos. 38, 39, and 40 show portable barriers evaluated to containment levels H1, H2, and H3, respectively. Very high containment level barriers, evaluated to H4a and H4b, are shown in Tables 41 and 42, respectively. Test names were not found for full-scale crash tests performed to EN 1317-2 criteria, therefore, barrier names were included.

Table 34. EN 1317-2 Containment Level T1

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
CB 240 [140]	Concrete	Key and Keyway	Safety Shape	No	None	Pass	Not Listed	7.9	1.3	7.9
SB 50 [141]	Concrete	Interlock	Vertical	No	None	Pass	Not Listed	7.9	2.1	19.7
DB 80AS-E [142]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	0.0	1.8	19.7
DB 65S [143]	Concrete with Steel Base	Key and Keyway	Single Slope	At Ends	None	Pass	Not Listed	3.9	1.7	19.7
DB 50SL [144]	Concrete with Steel Base	Key and Keyway	Single Slope	No	None	Pass	Not Listed	11.8	1.6	19.7
SteelPro 500 [145]	Steel	Interlock	NA	No	None	Pass	Not Listed	15.7	1.7	39.4
GuardVOX 500 [146]	Steel	Interlock	NA	No	None	Pass	Not Listed	16.5	2.5	44.0
GuardVOX 520 [146]	Steel	Interlock	NA	At Ends	None	Pass	Not Listed	7.9	2.5	44.0
GuardVOX 600 [146]	Steel	Interlock	NA	No	Top Mounted Rail	Pass	Not Listed	6.3	2.5	39.4
GuardVOX 800 [146]	Steel	Interlock	NA	No	Top Mounted Rail	Pass	Not Listed	1.6	2.4	39.4
GuardVOX 1200 [146]	Steel	Interlock	NA	No	Top Mounted Rail	Pass	Not Listed	3.9	3.4	39.4
VARIO-GUARD [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	3.9	1.3	39.4
VARIO-GUARD quick-joint [146]	Steel	Interlock	NA	At Ends	Top Mounted Rail	Pass	Not Listed	3.9	1.3	39.4
MINI-GUARD [146]	Steel	Not Listed	NA	No	None	Pass	Not Listed	18.5	1.0	44.3
Meton II [147]	Steel	Not Listed	NA	Not Listed	None	Pass	Not Listed	Not Listed	1.7	19.7
Meton III [147]	Steel	Not Listed	NA	Not Listed	None	Pass	Not Listed	Not Listed	2.1	19.7

Table 35. EN 1317-2 Containment Level T2

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
MINI-GUARD [146]	Steel	Not Listed	NA	No	None	Pass	Not Listed	50.8	1.0	44.3

Table 36. EN 1317-2 Containment Level T3

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
SB 50 [141]	Concrete	Interlock	Vertical	No	None	Pass	Not Listed	19.7	2.1	19.7
DB 80AS-E [142]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	11.8	1.8	19.7
DB 65S [143]	Concrete with Steel Base	Key and Keyway	Single Slope	At Ends	None	Pass	Not Listed	19.7	1.7	19.7
Meton I [147]	Concrete with Steel Base	Not Listed	Vertical	Not Listed	None	Pass	Not Listed	Not Listed	1.7	19.7
DB 50SL [144]	Concrete with Steel Base	Key and Keyway	Single Slope	No	None	Pass	Not Listed	19.7	1.6	19.7
Meton VII [147]	Steel and Concrete	Not Listed	NA	Not Listed	None	Pass	Not Listed	Not Listed	1.7	19.7
Meton IV Plus [147]	Steel and Concrete	Not Listed	NA	Not Listed	Not Listed	Pass	Not Listed	Not Listed	2.1	Not Listed
GuardVOX 500 [146]	Steel	Interlock	NA	At Ends	None	Pass	Not Listed	39.8	2.5	44.0
GuardVOX 520 [146]	Steel	Interlock	NA	At Ends	None	Pass	Not Listed	15.7	2.5	44.0
GuardVOX 600 [146]	Steel	Interlock	NA	No	Top Mounted Rail	Pass	Not Listed	15.4	2.5	39.4
GuardVOX 800 [146]	Steel	Interlock	NA	No	Top Mounted Rail	Pass	Not Listed	16.9	2.4	39.4
GuardVOX 1200 [146]	Steel	Interlock	NA	No	Top Mounted Rail	Pass	Not Listed	15.7	3.4	39.4
VARIO-GUARD [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	16.5	1.3	39.4
VARIO-GUARD quick-joint [146]	Steel	Interlock	NA	At Ends	Top Mounted Rail	Pass	Not Listed	11.8	1.3	39.4
MINI-GUARD [146]	Steel	Not Listed	NA	At Ends	None	Pass	Not Listed	90.6	1.0	44.3
Meton VI [147]	Steel	Not Listed	NA	Not Listed	None	Pass	Not Listed	Not Listed	1.7	19.7

Table 37. EN 1317-2 Containment Level N2

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Rebloc RB60H [148]	Concrete	Interlock	I-Shape	No	None	Pass	Not Listed	Not Listed	2.3	39.4
Rebloc RB80SA [148]	Concrete	Interlock	I-Shape	Yes	None	Pass	Not Listed	Not Listed	2.7	39.4
MultiBloc [148]	Concrete	Cross Bolt	Vertical	No	None	Pass	Not Listed	Not Listed	1.8	10.3
SB 50 [141]	Concrete	Interlock	Vertical	At Ends	None	Pass	Not Listed	51.2	2.1	19.7
SB 70 [149]	Concrete	Interlock	Vertical	At Ends	None	Pass	Not Listed	35.4	2.3	19.7
DB 80 [150]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	19.7	1.3	19.7
DB 80AS [151]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	39.4	1.7	19.7
DB 65S [143]	Concrete with Steel Base	Key and Keyway	Single Slope	At Ends	None	Pass	Not Listed	39.4	1.7	19.7
VARIO-GUARD [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	43.3	1.3	39.4

Table 38. EN 1317-2 Containment Level H1

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Rebloc RB80S [148]	Concrete	Interlock	I-Shape	No	None	Pass	Not Listed	Not Listed	2.7	39.4
DB 65S [143]	Concrete with Steel Base	Key and Keyway	Single Slope	At Ends	None	Pass	Not Listed	55.1	1.7	19.7
Meton I Plus [147]	Steel and Concrete	Not Listed	NA	Not Listed	Not Listed	Pass	Not Listed	Not Listed	2.5	Not Listed
Meton IV [147]	Steel and Concrete	Not Listed	NA	Not Listed	Not Listed	Pass	Not Listed	Not Listed	2.1	Not Listed
Meton IV Plus [147]	Steel and Concrete	Not Listed	NA	Not Listed	Not Listed	Pass	Not Listed	Not Listed	2.9	Not Listed
GuardVOX 520 [146]	Steel	Interlock	NA	At Ends	None	Pass	Not Listed	55.1	2.5	44.0
GuardVOX 800 [146]	Steel	Interlock	NA	At Ends	Top Mounted Rail	Pass	Not Listed	37.0	2.4	39.4
GuardVOX 1200 [146]	Steel	Interlock	NA	At Ends	Top Mounted Rail	Pass	Not Listed	39.8	3.4	39.4
VARIO-GUARD [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	54.7	1.3	39.4
VARIO-GUARD bolted [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	37.4	1.3	39.4
SoloGuard [146]	Steel	Not Listed	NA	Not Listed	Top Mounted Rail	Pass	Not Listed	27.6	Not Listed	Not Listed

Table 39. EN 1317-2 Containment Level H2

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Rebloc RB80H [148]	Concrete	Interlock	Safety Shape	None	None	Pass	Not Listed	Not Listed	1.4	26.2
Rebloc RB80A [148]	Concrete	Interlock	Safety Shape	Yes	None	Pass	Not Listed	Not Listed	1.9	26.2
Rebloc RB84XEAL [148]	Concrete	Interlock	Safety Shape	Yes	None	Pass	Not Listed	Not Listed	1.4	26.2
DB 80AS-E [142]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	11.8	1.8	19.7
DB 80 [150]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	43.3	1.3	19.7
DB 80AS-R Step [152]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	35.4	2.2	19.7
DB 80F [153]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	7.9	1.3	19.7
DB 80AS [151]	Concrete	Key and Keyway	Safety Shape	No	None	Pass	Not Listed	7.9	1.7	19.7
DB 90 Step [154]	Concrete	Key and Keyway	Single Slope	No	None	Pass	Not Listed	51.2	1.7	19.7
DB 80AS-A [155]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	3.9	1.7	19.7
DB 80A [156]	Concrete	Interlock	Safety Shape	Yes	None	Pass	Not Listed	7.9	1.3	19.7
DB 80E [157]	Concrete	Interlock	Safety Shape	Yes	None	Pass	Not Listed	3.9	1.3	19.7
DB 80AS-F [158]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	15.7	1.7	19.7
DB 80AS-R [159]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	27.6	1.7	19.7
DB 100 [160]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	59.1	1.4	19.7
GuardVOX 800 [146]	Steel	Interlock	NA	At Ends	Top Mounted Rail	Pass	Not Listed	51.2	2.4	39.4
VARIO-GUARD [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	76.0	1.3	39.4
VARIO-GUARD quick-joint [146]	Steel	Interlock	NA	At Ends	Top Mounted Rail	Pass	Not Listed	95.3	1.3	39.4
VARIO-GATE [146]	Steel	Not Listed	NA	At Ends	Top Mounted Rail	Pass	Not Listed	3.9	1.3	65.6
VARIO-CONNECT [146]	Steel	Not Listed	NA	At Ends	None	Pass	Not Listed	23.6	2.0	Not Listed
MotionGuard ITPC [146]	Steel	Not Listed	NA	Not Listed	None	Pass	Not Listed	47.2	Not Listed	Not Listed

Table 40. EN 1317-2 Containment Level H3

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
DB 100S [161]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	55.1	1.6	19.7

Table 41. EN 1317-2 Containment Level H4a

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
Rebloc RB140SFS [148]	Concrete	Interlock	Safety Shape	No	None	Pass	Not Listed	Not Listed	1.9	18.0
DB 100 [160]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	55.1	1.4	19.7

Table 42. EN 1317-2 Containment Level H4b

Barrier Name	Matl	Conn	Shape	Anchor	Retrofit	Pass/ Fail	IS (kip-ft)	Def (in.)	HW Ratio	Length (ft)
DB 100 [160]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	86.6	1.4	19.7
DB 120S-F [162]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	Not Listed	1.8	19.7
DB 120S-A [163]	Concrete	Interlock	Safety Shape	Yes	None	Pass	Not Listed	3.9	1.8	19.7
DB 110 [164]	Concrete	Key and Keyway	New Jersey	At Ends	None	Pass	Not Listed	43.3	1.6	19.7
DB 120S [165]	Concrete	Key and Keyway	Safety Shape	At Ends	None	Pass	Not Listed	35.4	1.8	19.7
DB 100AS-R [166]	Concrete	Key and Keyway	Safety Shape	Yes	None	Pass	Not Listed	35.4	1.7	19.7

2.5 Portable Barrier Simulations

Because many variations of portable barriers exist but not all have been full-scale crash tested, a research project was undertaken to perform simulations of portable barriers according to NCHRP Report 350 test no. 3-11 to evaluate a total of 160 unique barrier installations [167]. Previous research showed test no. 3-10, performed with the small car, resulted in acceptable performance and lower deflections than crashes performed at test no. 3-11. Therefore, all simulations were performed according to test no. 3-11 test conditions.

System variables included shape, segment length, width, and connection. Five barrier shapes were evaluated: F-shape, New Jersey, single slope, vertical, and inverted. Four segment lengths were evaluated: 6 ft, 10 ft, 12 ft, and 20 ft. Two variations of each barrier shape were evaluated: normal, as shown in Figure 39, and wide, as shown in Figure 40. All barrier profiles, normal and wide versions, were 32 in. tall.

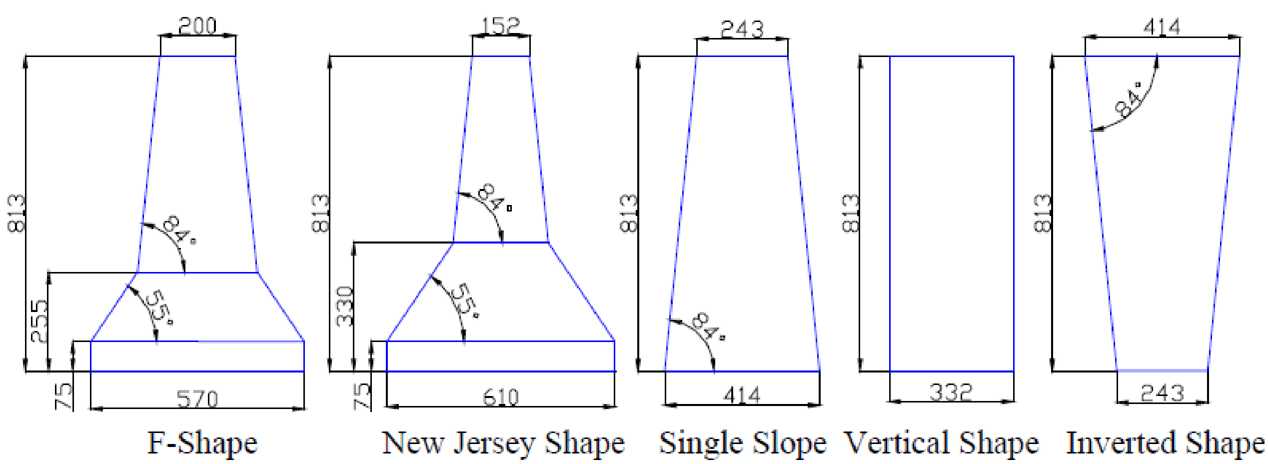


Figure 39. Barrier Shapes – Normal Width (mm) [167]

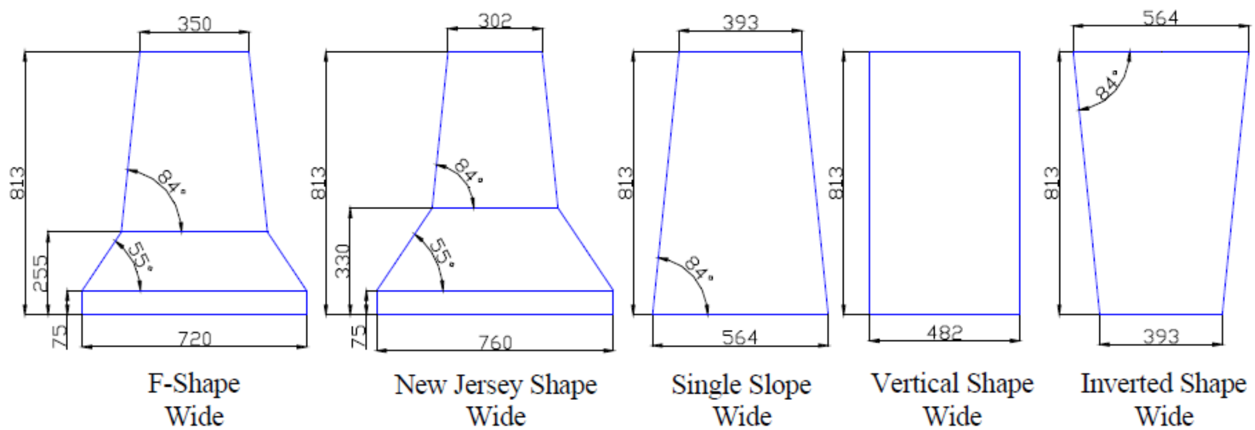


Figure 40. Barrier Shapes – Wide Width (mm) [167]

The pin and loop connection was the only connection evaluated through simulations. Two variables regarding the connection were explored: barrier gaps and hook distances. Barrier gaps were either open or closed, as shown in Figure 41. The open gap is preferred for installation purposes, but a closed gap configuration would provide the maximum moment carrying capacity for a pin and loop connection. The hook distances were either close or far, as shown in Figure 42.

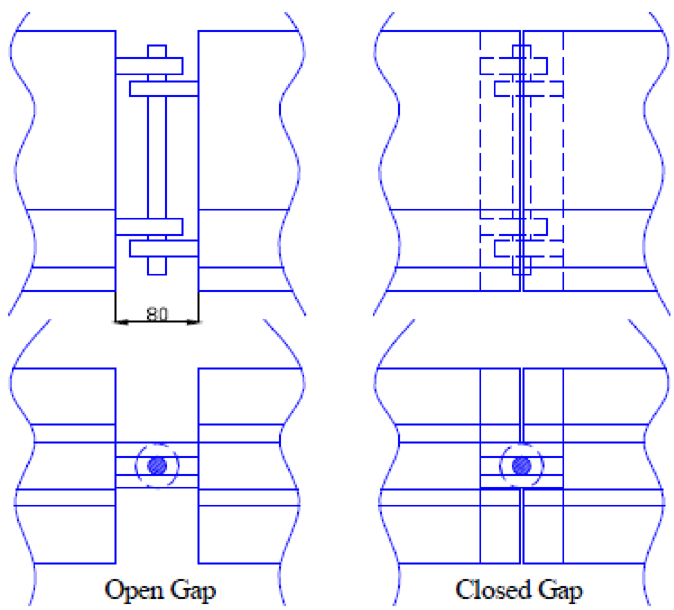


Figure 41. Barrier Gap [167]

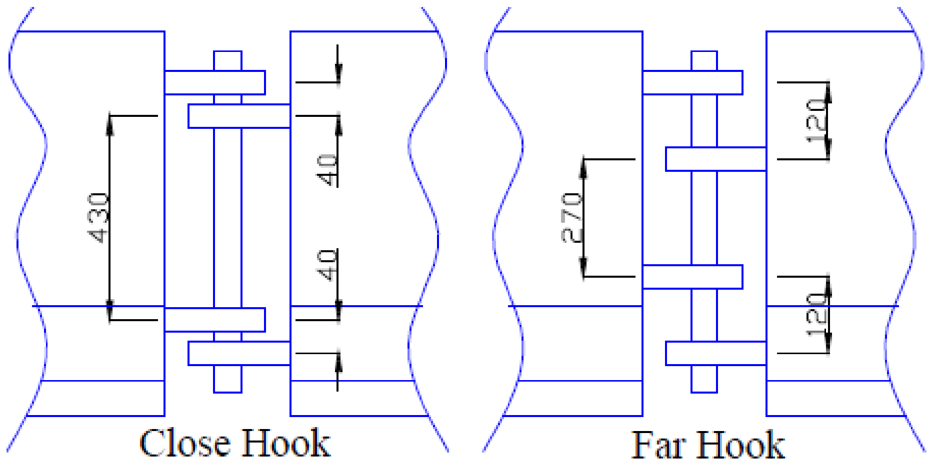


Figure 42. Hook Distance [167]

A total of 160 simulations were performed featuring various combinations of PCB shape, barrier length, barrier width, barrier gaps, and hook distances. Three of the simulations featured existing, previously full-scale crash tested systems: the Indiana PCB (F-shape, 10-ft segment length, wide, closed gap, close hook), the Iowa PCB (F-shape, 12-ft segment length, normal, open gap, close hook), and the Ohio PCB (New Jersey, 10-ft section length, normal, open gap, close hook). These three simulations were compared to their corresponding full-scale crash tests and were found acceptable. This in turn validated results from the remaining 157 simulations.

Table 43. Simulation Variables [167]

Characteristic	**Variables**
PCB Shape	F-Shape New Jersey Single Slope Vertical Inverted
Barrier Length	6 ft 10 ft 12 ft 20 ft
Barrier Width	Narrow Wide
Barrier Gaps	Open Gap Closed Gap
Hook Distances	Close Hook Far Hook

Many of the 160 PCB designs performed acceptably under simulated NCHRP Report 350 test no. 3-11 testing conditions regarding structural adequacy, occupant risk, and post-crash vehicle trajectory. If was found that narrow F-shape PCB had the best overall behavior. Longer segment lengths resulted in lower barrier deflections. The New Jersey shape barrier had a higher tendency for vehicle rollover compared to vertical, single slope, and inverted shapes. Consequently, the vertical, single slope, and inverted shapes resulted in higher ride-down accelerations.

2.6 Portable Barrier Costs

TTI performed a portable barrier cost comparison in the 1980s [168]. Ten different PCB systems were analyzed. Each was assumed to have the same shape but different joint connections. Segment lengths of 10, 20, and 30 ft were investigated.

Site visits were performed to collect information regarding installation times and man hours with respect to each type of PCB joint connection. From this information, cost estimates and relocation costs were calculated. Fabrication costs for the PCBs and joints were also calculated, in addition to one year of maintenance costs.

The total cost for each barrier was calculated and the least costly design was a 30-ft section PCB with a vertical pin with rebar (pin and loop). For 10-ft and 20-ft section lengths, the pin and loop design was also the least expensive of the ten designs.

3 ALTERNATIVE CONCRETES

Concretes alternatives to plain Portland cement concrete are in use in many fields and offer improved performance over regular concrete. These alternative concretes include ultra-high-performance concrete (UHPC), fiber reinforced concrete (FRC), and polymer concrete (PC). Cost information was not found for all types of alternative concrete, but the literature noted all would have higher costs than standard concrete.

3.1 Ultra-High-Performance Concrete

UHPC utilizes a low water-to-binder ratio, high binder content, steel fibers, and fine aggregate to achieve enhanced mechanical properties, durability, and workability [169]. These enhanced properties arise from the type of materials added to the mix, the mixing process, and the post-process [170]. However, UHPC costs approximately two to three times that of regular concrete [171], making it an unlikely candidate for the new portable barrier design. Mechanical properties of UHPC are shown in Table 48. A study performed for the Nebraska Department of Transportation (NDOT) determined the feasibility of developing an economic, non-proprietary UHPC mix due to current mixes costing approximately $2,000 per cubic yard [169]. This study noted that adding fibers to UHPC increases the tensile capacity and ductility, which reduces the propagation of cracks. The UNL UHPC mix cost approximately $700 per cubic yard and the mix design is shown in Table 44.

Table 44. Ingredients and Mix Design for UNL UHPC Mix [169]

Material	Type	Mass (lb/yd^3)
Sand	No. 10 Silica Sand	1,612
Cement	Type I/II	1,214
Slag	Grade 100 Slag	588
Silica Fume	Force 10,000 Densified Microsilica	162
Fiber	Dramix OL 13/.20 Micro Steel Fiber	266
High Range Water Reducer (HRWR)	Premia 150	55.6

Flow tests found that this mix has sufficient flowability and stability. It also demonstrated excellent mechanical properties, durability, and structural capacity, similar to commercially available UHPC. However, due to the need for high mixing energy, special mixers and procedures are required for UNL UHPC.

3.2 Fiber Reinforced Concrete

Fiber reinforced concrete (FRC) consists of standard concrete with some type of fiber material added. Desired concrete properties can be achieved with certain fiber additives and inclusion percentages. Typically, FRC is utilized in place of rebar reinforced concrete in certain applications where the concrete does not supply structural support [172]. Some applications include slabs on grade, pavement, overlays, composite steel decks, shotcrete, walls, and precast units. FRC can also be used in combination with rebar-reinforced concrete. Primarily, the purpose of fiber reinforcement is crack control. Concrete manufacturers can reduce or substitute traditional reinforcement with fiber reinforcement [173].

3.2.1 Fibers

Metallic, synthetic, and natural fibers are utilized in FRC, and the most common for construction are steel and synthetic. Microfibers have a diameter of less than 0.01 in. and are used to control plastic shrinkage cracks but do not add structural capacity to the concrete [174]. Macro fibers have diameters greater than 0.01 in. and are used to control shrinkage and temperature cracks in addition to increasing post-crack load bearing capacity and enhancing structural performance. Synthetic fibers include polypropylene (PP), polyvinyl alcohol (PVA), polyolefin (PO), polyethylene (PE), polyester, nylon, and glass.

Information regarding type of fiber was collected from Dr. Jiong Hu, an associate professor in the Civil and Environmental Engineering Department at the University of Nebraska-Lincoln (UNL) and is summarized here. For metallic fibers, the best improvement in properties result from using fibers with a high aspect ratio and fibers with hook ends or deformations [175]. Glass fibers have durability issues. Because they are easy to deform, nylon fibers are not good for mechanical property improvement. The used of PP fibers is typically to control shrinkage cracking, not to improve mechanical properties. Lastly, hemp fibers result in consistency issues. According to Dr. Hu, combining different types of fibers would further improve properties [175]. Additionally, he noted that if fibers are used in a concrete mix, a higher quantity of fine particles would be required to fill the interstices between aggregates, as shown in Figure 43.

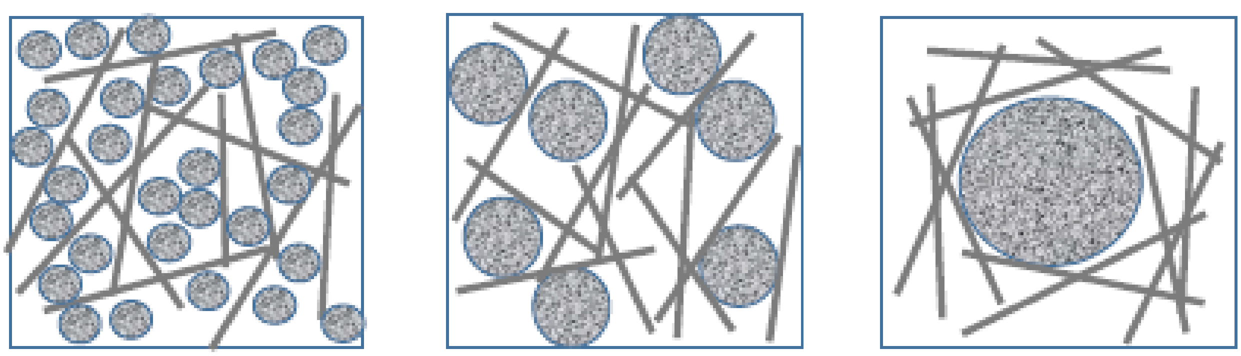


Figure 43. Fibers with Fine, Medium, and Large Sized Aggregates [176]

A thesis from Iowa State University, entitled *Fiber Reinforced Concrete: Tailoring Composite Properties with Discrete Fibers* [177], reviewed fibers used in FRC. Plain steel fibers may corrode when exposed to outdoor environments, so galvanized steel or stainless steel fibers can be used. However, steel fibers cost less than other high strength fibers by weight. PP fibers are chemically stable with concrete and are relatively low cost. Nylon fibers absorb water, so only low volume additions are recommended. Additionally, nylon fibers are more expensive than PP. PVA fibers increase toughness and ductility when added to concrete and improve post crack residual strength, but are more expensive than most other fibers. PO fibers increase post crack residual strength but not nearly as much as PP fibers. PO fibers are uncommon and are approximately the same price as PP fibers. Carbon fibers are very expensive and improvements in mechanical properties depend on the fiber quality. PE fibers improve post crack flexural ductility but are not often used due to their high cost. Acrylic fibers have been used and provide similar improvements as other cheaper fibers. Despite aramid fibers providing better performance compared to other fibers, they are not often used due to their high cost. Silica glass improves short term strength and ductility but degrades over time. It also is relatively inexpensive. Basalt glass fibers are uncommon but are expected to gain popularity due to their ability to increase flexural and tensile strengths and control cracking. Finally, this thesis noted that hybrid fiber dosage, or combinations of different types of fibers, showed promising results in laboratory experiments. Some mixing and manufacturing complications arose and no cost information was provided.

Various research has found that 1.0 percent by volume of synthetic fiber performs equivalent to 0.5 percent by volume of steel fiber [178]. The synthetic fiber was not specified, nor was size of the synthetic or steel fibers. It was also noted that the larger percentage of synthetic fibers decreases the workability of the material more than the smaller percentage of steel fibers.

3.2.2 Advantages

FRC offers many advantages over standard concrete. Fibers control cracks, reducing their size and depth. In addition, when impacted, fibers reduce the amount of spalling and chipping. Smaller cracks reduce chemical penetration into the concrete. These advantages result in more durable concrete, which results in a longer service life and/or reduced maintenance costs. In addition, adding fibers increases the toughness of concrete and holds specimens together after cracking, which is not necessarily the same as increasing the strength. Fibers also prevent material disintegration.

3.2.3 Disadvantages

When fibers are added to concrete, the workability of the concrete decreases. However, the same mixing and manufacturing processes and equipment can generally be used for regular concrete and FRC. Another disadvantage of FRC compared to regular concrete is the cost of the fibers. Thus, while changes to the manufacturing process does not typically incur additional costs when fibers are added, there is a cost increase due to the cost of the fibers [171].

3.2.4 Manufacturing

FRC does tend to require different manufacturing considerations. For example, stiff fibers tend to protrude from sharp corners [176]. Additionally, when fibers are used in combination with rebar reinforcement, the fiber length should not exceed ½ the clear minimum spacing between rebar.

A report by South Dakota State University, entitled *Fiber-Reinforced Concrete for Structure Components* [171], reviewed FRC manufacturing for various structural components. Within this report, five fiber additives were reviewed and described, as shown in Table 45. Four of the fibers were synthetic and one was steel. TUFF-STRAND SF is a mixture of PP and PE fiber and FORTA-FERRO fibers are PP. The type of synthetic materials from which Strux 90/40 and Fibermesh 650 fibers are made were not identified.

Physical properties, recommended dosage rates, manufacturer recommendations, and cost are shown in Table 45. The steel fibers were less expensive than any of the synthetic options, at

$1.19 per lb compared to $5.00 or $6.00 per lb. The only fiber which was recommended for use in precast elements, such as portable barriers, was the FORTA-FERRO fiber.

The volume of a rectangular barrier with a 32-in. height, 16-in. width, and 12.5-ft (150-in.) length is 1.64 yd^3. Table 46 shows the minimum and maximum cost for adding fibers to this rectangular barrier for the recommended synthetic fiber FORTA-FERRO and the steel fiber Dramix 5D. Adding FORTA-FERRO fibers will result in an approximate additional cost between $25 and $250 per barrier section, depending on the determined dosage. Using steel fibers will result in a minimum additional cost of approximately $50 per barrier section. Note, no maximum dosage for steel fibers was provided.

Table 45. Fiber Information [171]

Fiber	Strux 90/40	Fibermesh 650	TUF-STRAND SF	FORTA-FERRO	Dramix 5D
Manufacturer	W.R. Grace	Propex Fibermesh	Euclid Chemical Company	Forta Corporation	Bekaert
Fiber Class	Synthetic	Synthetic	Synthetic	Synthetic	Steel
Length (in.)	1.55	1.5 to 1.75 blend	2.0	1.5 to 2.25 blend	2.4
Equivalent Diameter (in.)	0.017	0.016 to 0.018	0.027	0.028, 0.019	0.04
Aspect Ratio*	90	96.5	74	79.5	65
Specific Gravity	0.92	0.91	0.92	0.91	7.85
Tensile Strength (ksi)	90	89	87 to 94	83 to 96	333.5
Modulus of Elasticity (ksi)	1,378	1,088	1,380	690	30,000
Recommended Dosage Rate (lb/yd^3)	3 to 12	3 minimum	3 to 20	3 to 30	25 minimum
Manufacturer Recommended Applications	Overlays, Slab-On-Grade, Pavements, Composite Steel Floor Decks	Overlays, Slab-On-Grade, Pavements, Composite Metal Decks	Toppings, Slab-On-Grade, Pavements, Thin Walled Pre-Cast	Bridge Decks, Industrial Floors, Pre-Cast Products, Shotcrete	Bridges, Structural Floors, Foundation Slabs
Cost ($/lb)	6.00**	5.00**	6,00**	5.00**	1.19

* Aspect Ratio = fiber length divided by equivalent fiber diameter
** Cost was estimated by fiber manufacturers based on typical material and labor costs

Table 46. FORTA-FERRO and Dramix 5D Fiber Cost for Minimum and Maximum Dosages

Fiber	**Dosage**	**Dosage (lb/yd^3)**	**Amount of Fibers (lb)**	**Cost ($ per barrier section)**
FORTA-FERRO (PP)	Minimum	3	4.92	24.60
	Maximum	30	49.2	246.00
Dramix 5D (steel)	Minimum	25	41	48.79

Recommendations for fiber dosage and FRC design are shown in Table 51 [171]. These recommendations resulted from testing featuring the fibers listed in Table 45. For the fibers tested for that research, the FORTA-FERRO fiber was recommended due to its cost effectiveness and low aspect ratio, which minimizes fiber balling when mixing. A minimum fiber volume fraction of 0.2 percent was recommended based on manufacturer suggestions.

Table 47. Fiber Dosage and FRC Design Recommendations [171]

For	**Recommendation**	**Justification**
Fiber Dosage Recommendations	Fibers with low aspect ratios should be used (less than 100, but not less than 40)	Minimize fiber balling
	Steel fibers should be avoided in components that would be exposed to chloride penetration	Susceptibility to corrosion
	Among the tested synthetic fibers, FORTA-FERRO should be used	It is cost effective and has low aspect ratio
	Minimum fiber volume fraction should be 0.2%	Manufacturer suggestion and lack of data for lower dosages
	The minimum fiber dosage that satisfies required properties should be chosen	Ensure cost-effectiveness and higher slump values
FRC Design	Higher slump values, compared with PCC mixes, should be targeted for FRC mixes	To compensate for the reduced workability of FRC mixes
	Fine to coarse aggregate ratio should be increased	To provide higher mortar content that is helpful in increasing workability, minimizing fiber balling, and reducing crack widths
	Up to 20% and 15% reduction in compressive strength and modulus of elasticity, respectively, should be taken into consideration when designing FRC mixes	This reduction was observed in the data

Additional mechanical property information for normal concrete, FRC, and UHPC were provided by Dr. Hu and are shown in Table 48. From this information, it was determined that the main advantage of alternative concretes is crack resistance [176]. UHPC showed a significant increase in compressive and flexural strength, however, the increased flexural strength would not likely be sufficient for developing the capacity required for a portable barrier to meet MASH TL-3 impact loading without adding traditional reinforcing steel. The main benefit of UHPC or FRC for a new portable barrier would be crack resistance, and, if possible, spall reduction. Both PP and steel FRC showed high crack resistance, but it was not clear if the added crack resistance would offset the additional cost.

Table 48. Alternate Concrete Properties [176]

Concrete	Fiber (by volume)	Compressive Strength (psi)	Flexural Strength (psi)	Elastic Modulus (ksi)	Chloride Penetration (coulomb)	Crack Resistance
Normal Concrete	-	3,000 to 6,000	400 to 600	2,000 to 6,000	>2,000	Very Low
FRC	<0.5% PP	3,000 to 6,000	400 to 600	2,000 to 6,000	>2,000	High
	0.5-1.5% macro steel	3,000 to 6,000	500-1,000	2,000 to 6,000	>2,000	High
UHPC	>2% micro steel	>22,000	1,000 to 3,000	8,000 to 10,000	20 to 360	Extremely High

Various concrete additives were also researched and information was collected and summarized in Table 49. Fiber additives include rock, carbon, metal, glass, plant, nylon, polyester, and PP and other additives include fly ash, silica fume, and nano-MMT particles. Certain additives increased and decreased properties of concrete, had effects on workability, and reduced water absorption.

Table 49. Fiber Reinforcement Advantages and Disadvantages

Add-In	Increase	Decrease	Notes
Basalt Fiber	Deformation [179] Energy Absorption Capacity [179] Compressive Strength [180, 181] Flexural Strength [182] Tensile Strength [180-182] Number of Blows [179]	Workability [181, 182] Compressive Strength (at late age) [182]	-
Carbon and Steel Fiber	Flexural Strength [183] Tensile Strength [183] Flexural Toughness (more than carbon or steel alone) [183]	-	-
Carbon Fiber	Compressive Strength [183, 184] Tensile Strength [183] Ductility [184]	-	No effect on compressive properties [185]
Fly Ash	Structural Integrity [186]	Compressive Strength [186, 187]	Recommend maximum of 15% inclusions [187, 188] Does not affect workability [187]
Glass Fiber	Flexural Toughness [189] Compressive Strength [181, 184, 185 190, 191] Flexural Strength [190, 192, 193] Toughness [191, 194] Failure Strain [185, 191] Ductility [184]	Workability [181] Compressive Strength [192]	Recommend 0.75% inclusions [181]
Hemp Fiber	Compressive Strength [195] Flexural Strength [195] Flexural Toughness [195] Toughness Index [195]	Compressive Strength [196]	-
Kenaf Fiber	Energy Absorption [197]	-	-

Table 50. Fiber Reinforcement Advantages and Disadvantages (Cont.)

Add-In	Increase	Decrease	Notes
Metallic Fiber	Workability [198] Mechanical Properties [198] Fracture Strength [198] Flexural Strength [198]	-	-
Nylon Fiber	Tensile Strength [199] Flexural Strength [193, 199] Fracture Strength [199]	-	-
Polyester, Steel, and PP Fiber	-	-	Does not affect volume weight [200]
PP Fiber	Compressive Strength [187, 201-204] Fracture Energy [205] Mechanical Properties [206] Flexural Strength [207] Flexural Toughness [207] Tensile Strength [201, 202] Modulus of Rupture [201] Toughness Index [201] Impact Strength [204]	Workability [186, 187, 208] Compressive Strength [205] Flexural Strength [205] Weight [186]	Recommend 1.5% inclusions [202]
Silica Fume	Compressive Strength [204, 209] Number of Blows [209] Brittleness [209] Mechanical Properties [206] Bond Strength [210] Pullout Energy [210] Fiber Dispersion [204]	Water Absorption [206]	-
Silica Fume and PP Fiber	Compressive Strength [204] Tensile Strength [204] Flexural Strength [204]	-	-
Silica Fume and Steel Fiber	Compressive Strength [209] Tensile Strength [209] Flexural Strength [209]	-	-
Steel and PP Fiber	Tensile Strength [207] Flexural Strength [207]	-	-
Steel Fiber	Compressive Strength [187, 188, 192, 207, 209, 211-215] Flexural Strength [192, 193, 205, 207, 211, 214, 216-218] Flexural Toughness [183] Tensile Strength [187, 209, 211, 213, 214, 219] Energy Absorption Capacity [219] Weight [212] Impact Resistance [211] Fracture Toughness [214] Mechanical Properties [206] Fracture Energy [205] Ductility [188]	Workability [187, 212]	Recommend longer fibers [210] Recommend hooked fibers [210] Recommend only steel fibers or with 12% PP fibers [189]
Nano-MMT Particles	Flexural Strength [220] Tensile Strength [220]	-	-
Copper Coated Stainless Steel Fiber	Compressive Strength [221]	-	-

3.2.5 Manufacturer Input

MwRSF contacted local manufacturer Concrete Industries and collected their input regarding FRC and/or alternative concretes, as shown in Table 51 [222]. No cost or strength information was provided. The level of experience with each type of additive or material was noted. It was noted that Concrete Industries' current experience with FRC was limited, and concerns existed with respect to the use of certain fibers or additives with their fabrication and mixing equipment.

Table 51. Fiber Reinforced Concrete Information from Concrete Industries [222]

Fiber	Experience	Notes
Basalt	No Experience	-
Carbon and Steel	No Experience	Not tested due to contamination fears with electronic mechanisms.
Carbon	No Experience	Not tested due to contamination fears with electronic mechanisms.
Fly Ash (not fiber)	Large Amounts of Experience	Problems with Class F and 28-day strength development. Class C ash used up to 30%.
Glass	Currently using Cem-FIL Mini-Bars [223] in exterior wythe of insulated wall panels to control cracking.	-
Hemp	No Experience	-
Kenaf	No Experience	-
Nylon	No Experience	-
Polyester, Steel, and PP	Have Not Used This Combination	-
PP	Used Routinely for Crack Controls	-
Silica Fume (not fiber)	Used in Past, but Not Much Recently	Difficult to work with and requires special finishing techniques. Strengths are great if properly controlled and cured.
Silica Fume and PP	Have Not Used This Combination	-
Silica Fume and Steel	Have Not Used This Combination	-
Steel and PP	Have Not Used This Combination	-
Steel	Some Experience	Adds to flexural capacities.
Nano-MMT Particles	No Experience	-
Copper Coated Stainless Steel	No Experience	-

3.3 Polymers in Concrete

Polymer concrete additives are made up of two chemical compounds: resin and hardener [224]. When polymers are used in concrete applications, they become the binding agent in place of cement. In some cases, polymers are combined with cement and added to the concrete mix, resulting in polymer impregnated concrete, polymer Portland cement concrete, or polymer modified concrete (PMC). Fiber reinforced polymer bars have also been used in lieu of steel reinforcing bars.

3.3.1 Polymer Concrete

Polymer concrete (PC) uses polymer as a binding agent instead of cement. These concretes feature improvements in mechanical properties with an associated increase in cost. PC was found to have compressive strengths between 7,252 and 18,855 psi, flexural strengths between 1,450 and 6,527 psi, and tensile strengths between 1,160 and 1,740 psi. In addition, PC has been used in precast elements [224].

Common resins include polyester, methyl methacrylate, epoxy, furan, polyurethane, and urea formaldehyde. Due to lower relative cost, availability, and mechanical properties, polyester resins are very common [225]. Epoxy resins result in better mechanical properties and durability compared to polyester resins but are more expensive. It was found that microfillers and silane coupling agents, when added to polymer concretes with polyester resin, can improve properties to the level of those with epoxy resin [226]. Properties and experimental findings of polymer concretes with various aggregates and epoxy or polyester resins are listed in Tables 52 and 53, respectively.

Advantages of PC include improved cracking strength, improved durability, low permeability to water and salts, and good corrosion resistance. PC can expand and contract over time to accommodate temperature changes, which results in greater resistance to thermal cracking than regular concrete [227]. The main disadvantage of PC is cost, with one report noting PC is too expensive to use in large projects [227]. It also has a lower compressive strength than normal concrete. Unlike FRC, PC may require special equipment to manufacture.

Table 52. Polymer Concrete with Epoxy Resin

Aggregate	Increase	Decrease	Notes
Crushed Quartzite, Siliceous Sand, Calcium Carbonate	Compressive Strength by 36% with silane coupling agent [226]	-	Better properties than polyester resin [226]
Ottawa Sand, Blasting Sand	Flexural Strength by 25% with silane treatment [190] Compressive Strength with curing temperature [228]	-	Maximum compressive strength and flexural strength found at 14% resin content [190]
Coarse and Fine Aggregate	-	-	Maximum compressive strength and highest modulus of rupture at 12% resin content [229]
Clean Sand, Foundry Sand, Calcium Carbonate	-	-	Foundry sand provided better properties than clean sand [230]
River Gravel, Silica Fume	-	-	Compressive Strength between 43.4 and 65.3 MPa, flexural strength between 12.3 and 17.5 MPa, 15.6% resin content was suitable for almost all properties [231]
Gravel, Sand	-	-	Maximum compressive strength and flexural strength at 13% resin content obtained after 3 days of curing [232]
Sand, Mesh, Pebble	-	-	Optimum mix 50% pebble, 42.5% sand, 7.5% resin [233]
Basalt, Quartzite	-	-	Maintains damping over a large frequency range [234]
Crushed Stone, River Sand, Calcium Carbonate	-	-	Compressive strength and tensile strength decrease with temperature [235]
Crushed Stone, Fine Sand	Addition of 1% silane agent increases load for withstanding 2 million cycles [236]	-	Resin content does not affect compressive strength [236]
Crushed Quartzite, Siliceous Sand, Calcium Carbonate	Compressive strength by 30% with silane coupling agent [226]	-	-
Ottawa Sand	Compressive strength by 14% with silane treatment [238]	-	Compaction molding had better results than vibration molding [237] Maximum flexural and compression modulus were found at 14-16% resin content [237] Maximum compressive strength at 15% resin [238]

Table 53. Polymer Concrete with Polyester Resin

Aggregate	Increase	Decrease	Notes
Ottawa Sand, Blasting Sand	Flexural strength by 25% with silane treatment [190] Compressive strength with curing temperature [228]	-	Maximum compressive and flexural strength at 14% resin content [190]
Granite, River Sand, Fly Ash	-	High levels of fly ash decrease workability [239]	Good strength and resistance to water absorption up to 75% fly ash [239]
Crushed Granite, Sand, Calcium Carbonate	-	-	Compressive strength between 90 and 108 MPa [240]
Coarse and Fine Aggregate	-	-	Maximum compressive strength and highest modulus of rupture at 12% resin [229]
Clean Sand, Foundry Sand, Fly Ash	-	-	Best results at 20% resin content [241] Better properties with clean sand [230]
Pea Gravel, Sand, Fly Ash	Compressive strength by 30% when 15% sand is replaced with fly ash [242]	-	-
Andesite, River Sand, Calcium Carbonate	-	-	Maximum water content of 0.1% [243] Optimum mixture: 11.25% resin, 11.25% calcium carbonate, 29.1% andesite, 9.6% sand (1.2-5 mm) and 38.8% sand (<1.2 mm) [243]
Pea Gravel, River Sand, Fly Ash	-	-	Optimum mixture: 10% resin, 45% pea gravel, 32% sand, 13% fly ash [188] Achieved 80% strength after curing 1 day [188]
Sand, Gravel	-	-	Large damping factors over wide frequency range [244]

3.3.2 Polymer Modified Concrete

Polymer modified concrete (PMC) is typically concrete that has a combination of cement and some type of polymer [224]. These materials feature limited improvements in mechanical properties compared to the increased cost.

3.3.3 Fiber Reinforced Polymer

Fiber reinforce polymer (FRP) consists of strong, stiff fibers, such as glass, carbon, or aramid impregnated in polymeric resins [224]. One application of FRP is forming bars, which can be used in place of rebar for reinforcement. FRP reinforcement has been used successfully in several structural applications.

FRP degrades under sustained loading, moisture, variations in temperature, and alkalinity, which may make it unsuitable for use in PCB design [224]. The level of degradation depends on the type of fiber, type of resin, manufacturing process, and environment. Specifically, E-glass degrades in moisture and alkalinity. Carbon fibers are relatively inert. Aramid fibers degrade in moisture and ultraviolet (UV) light.

3.3.4 Manufacturer Input

Information from Concrete Industries about polymer concretes is shown in Tables 54 and 55 [222]. No cost or strength information was provided. The level of experience with each type of concrete was noted.

Table 54. Polymer Concrete with Epoxy Resin Information from Concrete Industries [222]

Fiber	As Used with Epoxy Resin	As Used in Standard Concrete
Crushed Quartzite, Siliceous Sand, Calcium Carbonate	No Experience	No Experience
Ottawa Sand, Blasting Sand		No Experience
Coarse and Fine Aggregate		Routinely Used in Daily Production
Clean Sand, Foundry Sand, Calcium Carbonate		No Experience
River Gravel, Silica Fume		No Experience
Gravel, Sand		NDOT 47B S&G is Considered a Combination of These Two Products
Sand, Mesh, Pebble		No Experience
Basalt, Quartzite		No Experience

Table 55. Polymer Concrete with Polyester Resin Information from Concrete Industries [222]

Fiber	As Used with Polyester Resin	As Used in Standard Concrete
Crushed Stone, River Sand, Calcium Carbonate	No Experience	No Experience
Crushed Stone, Fine Sand		Used Daily in Both Repair and Maintenance (RM) and Continual Improvement (CI) Structural Mixes
Crushed Quartzite, Siliceous Sand, Calcium Carbonate		No Experience
Ottawa Sand		No Experience
Ottawa Sand, Blasting Sand		No Experience
Granite, River Sand, Fly Ash		No Experience
Crushed Granite, Sand, Calcium Carbonate		No Experience
Coarse and Fine Aggregate		Used Daily in Both RM & CI Structural Mixes.
Clean Sand, Foundry Sand, Fly Ash		No Experience
Pea Gravel, Sand, Fly Ash		Used By Some in Shotcrete Situations as Part of the Overall Mix Design.
Andesite, River Sand, Calcium Carbonate		No Experience
Pea Gravel, River Sand, Fly Ash		Used By Some in Shotcrete Situations as Part of the Overall Mix Design.
Sand, Gravel		Used Daily in RM Mixes. Not Recommended for Exterior in this Combination. Alkali-Silica Reaction (ASR) issues.

3.4 Precast Examples

Alternative concretes have been used in precast elements. FRC was utilized in the manufacture of Jersey barriers, portable vehicle barriers for anti-ram perimeters, and tunnel segments. PC was used in thin panels for roadside barriers, pipes, and manhole covers.

3.4.1 Fiber Reinforced Concrete

3.4.1.1 Jersey Barriers

One project involved manufacturing Jersey barriers out of FRC [171], in which 3M PO fibers were utilized to reduce cracking. No cost or strength information was reported, but researchers recommended a higher slump than generally specified for concrete so the mixture can consolidate around steel reinforcing bars.

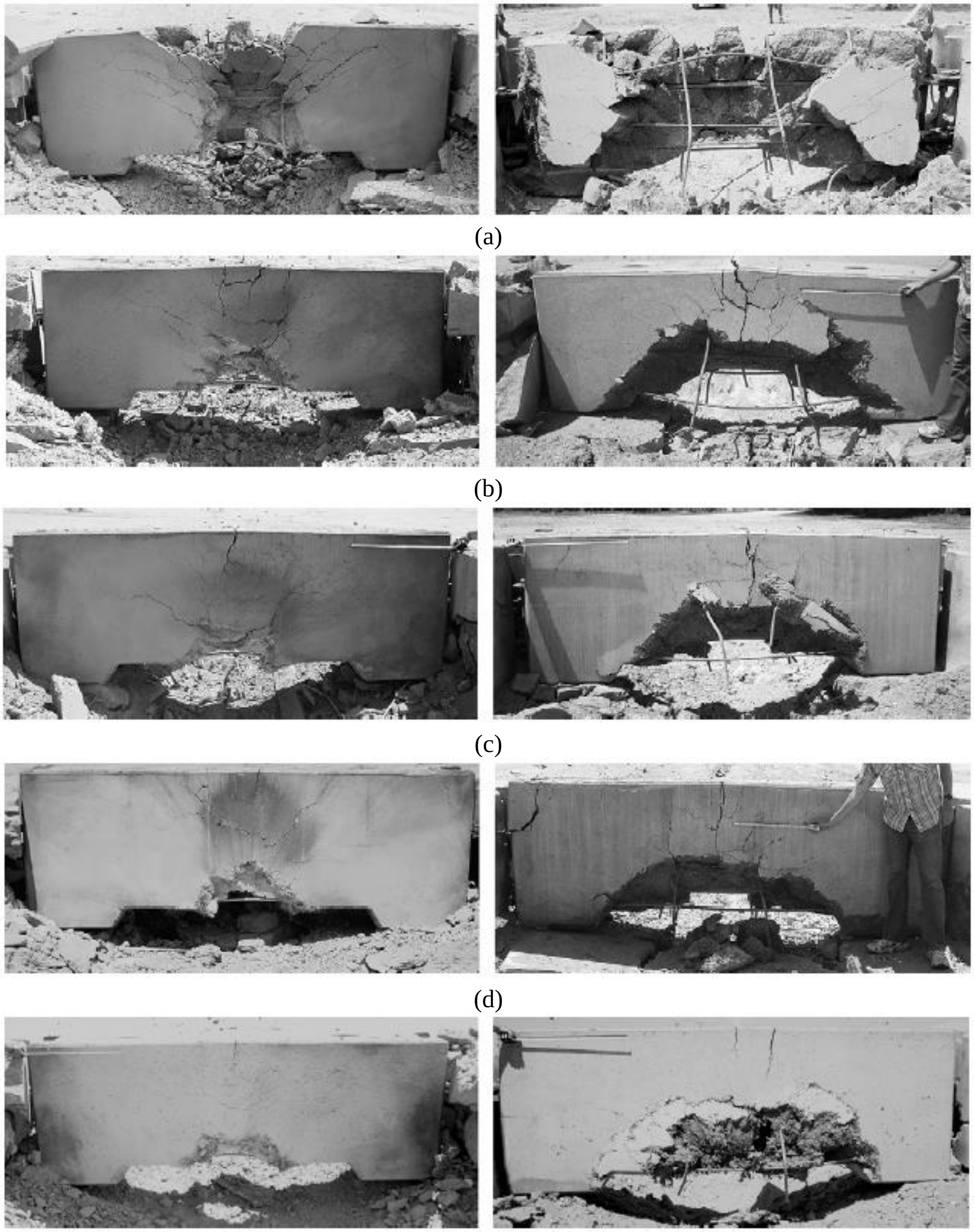
3.4.1.2 Portable Vehicle Barriers

Portable vehicle barriers, for use in anti-ram perimeters, were designed with fiber reinforcement and tested with explosives [245]. Five different barriers were manufactured, shown in Table 56 with their fiber contents. Barrier K-1 served as the control barrier because it featured no fiber reinforcement.

Table 56. Portable Vehicle Barrier Fibers [245]

Barrier	Concrete	Fiber Content
K-1	Standard Concrete	None
CFRC	Carbon Fiber	1.5% by Volume
NFRC	Nylon Fiber	1.5% by Volume
SS-H	Synthetic and Steel Fiber Mix 1 (High Fiber Volume)	2.5% by Volume 1.2 in. Long Flat End Steel Fibers 1.8% by Volume 2.0 in. Long PP/PE Fibers 0.6% by Volume Variable Length Macro PP Fibers 0.066% by Volume Variable Length Micro PP Fibers Total Fiber Volume = 5.0%
SS-L	Synthetic and Steel Fiber Mix 2 (Low Fiber Volume)	2.0% by Volume 1.2 in. Flat End Steel Fibers 1.33% by Volume 2.0 in. PP/PE Fibers 0.4% by Volume Variable Length Macro PP Fibers 0.066%by Volume Variable Length Micro PP Fibers Total Fiber Volume = 3.8%

These barriers were placed by a charge which was detonated, then barrier damage was reviewed. The control barrier, K-1, which featured no fiber reinforcement, sustained the most damage, as shown in Figure 44(a). The damage seen on the carbon and nylon fiber reinforced barriers, shown in Figures 44(b) and 44(c), was less severe than damage seen in the control barrier. Large craters were observed on the back side of each of these barriers, but the interior concrete was intact. The steel and PP fiber reinforced barriers showed the least extensive damage, as shown in Figures 44(d) and 44(e).



(a) (b) (c) (d) (e)

Figure 44. Portable Vehicle Barriers, Front (Left) and Back (Right), (a) K-1, (b) CFRC, (c) NFRC, (d) SS-H, and (e) SS-L [245]

Conclusions regarding fiber reinforcement were drawn from this study and are summarized below:

- FRC limits the extent of damage and keeps damaged concrete more intact than normal concrete in barriers exposed to contact charges. Traditional concrete was much more likely to become fragmented, which would greatly reduce its resistance to vehicle impact.

- Nylon FRC barriers at 1.5% fiber volume, the smallest increase in fiber volume that was studied, were shown to greatly improve performance over typically reinforced concrete barriers in terms of reduction of mass lost and superficial damage.

- The 3.8% steel and PP fiber mix (SS-L) performed to the same level as the 5% mix of the same fibers (SS-H), showing there is little performance improvement from increased fiber volume when fiber volume is already at a certain level. The fiber volume level where additional fibers do not result in performance improvements will likely occur below 3.8% for a steel and PP fiber blend concrete.

- High fiber surface area was found to increase the prevalence of large fragments in the debris field by holding debris together, result in increased fragment sizes.

3.4.1.3 Tunnel Segments

Tunneling segments, typically made of concrete with rebar reinforcement, were designed with steel fiber reinforcement and tested [173], as shown in Figure 45. The steel fibers had a diameter of 0.01 in. and a length of 1.2 in. The dosage was equal to 67.4 lb/yd^3.

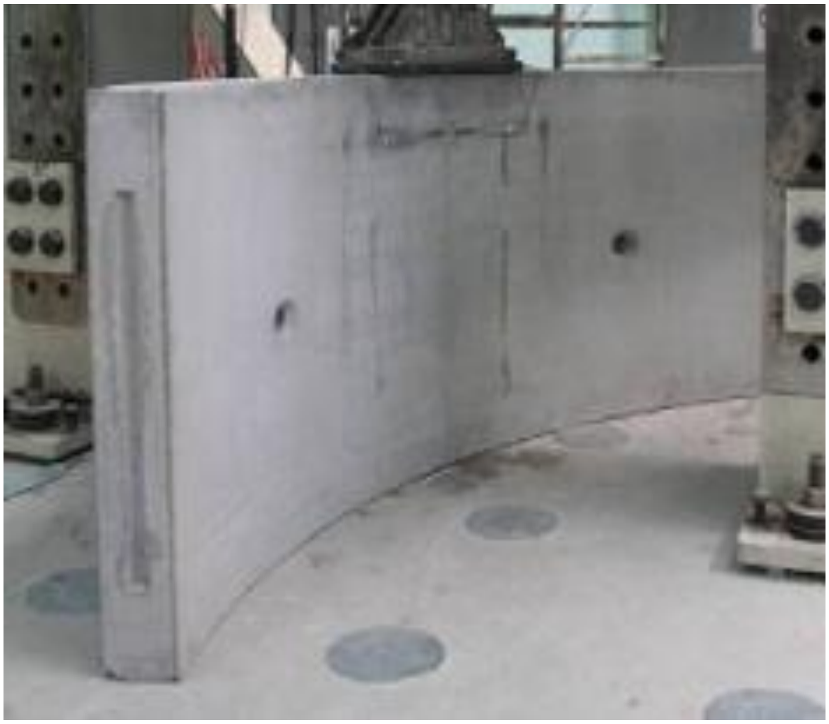


Figure 45. Tunnel Segment [173]

It was found that FRC could be used in place of traditionally reinforced concrete and featured improved crack control over regular concrete. However, careful design of the material and structure was needed to achieve the strength results. No cost information was provided, but it was noted that using FRC could lead to lower costs for this particular application.

3.4.2 Polymer Concrete

3.4.2.1 Thin Panels

Thin, precast PC panels were manufactured which used a polymer-based binder instead of Portland cement [224]. Because PC is expensive, thin sections were precast, which were then placed in front of regular concrete. Special mixing equipment was required to manufacture the PC components. The thin PC featured an internal FRP reinforcing mesh and a polyester resin gel coat was applied to the exposed face. It was noted that this project was expensive.

3.4.2.2 Pipes

A cost comparison between market prices for PC and regular concrete was performed for a pipe project [246]. It was found that PC pipes had a service life 3.3 times longer than pipes made from regular concrete. The average cost of PC was found to be $0.78 per lb and the average cost of regular concrete was $0.02 per lb. When a cost comparison was performed which took service life into consideration, it was found that PC pipes cost $6,860 per year while regular concrete cost $17,150 per year.

3.4.2.3 Manhole Covers

Manhole covers made from Portland cement and PC were compared in a study performed at the University of Nevada [247]. This study utilized cost information found in the pipe report, summarized in Section 3.4.2.2. The cement concrete manhole covers were found to have a service life of approximately 23 years, while the PC manhole covers had an estimated service life of 50 years based on manufacturer information. However, despite having a much higher cost, PC was determined to be 2.5 times more economical than regular cement due to the increased service life.

3.5 Discussion

Due to cost and need for special mixing equipment, UHPC is not recommended for the new portable barrier. If a less expensive version or new manufacturing methods arise, they could be considered. Polymer concrete may require special mixing equipment and was noted to be too expensive for large projects, making it an unlikely choice for the new portable barrier.

In terms of the use of other alternative concretes and fiber additives for the new portable barrier system, it appears unlikely that adequate barrier strength can be achieved without traditional steel reinforcement, but alternate concretes could be used to limit cracking, spalling, or other damage seen on the barrier due to transportation, installation, and impact. Further study may be needed to determine if the use of alternative concretes would be warranted based on a cost-benefit analysis. Thus, it may be worthwhile to design a new portable barrier system based on traditional concrete mixes for minimizing initial costs and ease of implementation. If desired, alternative concretes could be investigated once a barrier has been developed and put into service.

4 DESIGN CRITERIA SURVEY

4.1 Survey

A survey to prioritize portable barrier design criteria was sent to members of the Midwest Pooled Fund and other state DOTs, who were encouraged to forward the survey on to portable barrier fabricators, installers, and consultants. The survey was administered online using SurveyGizmo and distributed via email.

4.2 Questions

Survey questions are shown in Appendix A and are summarized in Sections 4.4.1 through 4.4.31. The first section of the survey inquired about portable barrier cost; respondents were asked to rank the importance of cost, if they would be willing to pay higher costs if durability or life cycle was increased, and an acceptable price per linear foot of barrier. The next section involved material choice. Respondents ranked reinforced concrete, steel, and plastic in preference, decided if concrete additives (such as fibers) should be considered for concrete, and commented if steel or plastic barriers should be ballasted. Next, respondents were asked to rank durability in terms of importance when the barrier is in the work zone, during transport, and during installation. Installation and operational concerns were addressed and ranked, and safety performance was ranked. Finally, anchorage options portable barrier systems were discussed.

4.3 Respondents

A total of 31 respondents gave complete responses to the survey questions. Responding organizations, including fabricators, installers, consultants, and state DOTs are listed in Table 57 in addition to the total number of respondents in each category. An additional 28 respondents began the survey but did not complete it. Therefore, those respondents and their responses were not included in the results.

Table 57. Survey Respondents

Organization	Respondent(s)	Number of Responses
Fabricator	Wieser Concrete Products, Inc. Brock White Construction Materials	3
Installer	Contractor (not specified) Zenith Tech, Inc.	3
Consultant	Consultant Engineering Firm Civil Consultant Michael Baker Kapur & Associates Doobiedoo	5
State DOT	Alabama Alaska California* Colorado Hawaii Maine Maryland Minnesota* Missouri* Nebraska* New Jersey* North Carolina* Ontario (Canada) Tennessee Utah* Virginia* Wyoming*	20
TOTAL	**-**	**31**

* Member of the Midwest Pooled Fund Program

4.4 Results

Survey results are summarized in Sections 4.4.1 through 4.4.31 and Figures 46 through 109. Total responses are shown in addition to responses sorted by responding organization. Organization responses are shown as numbers and percentages, to further illustrate organizational design priorities.

4.4.1 Question 1

The first question of the survey asked responders to rank cost as low, medium, or high importance with regards to the new portable barrier. The total response is shown in Figure 46. In total, 27 respondents (87 percent) ranked cost as medium or high importance.

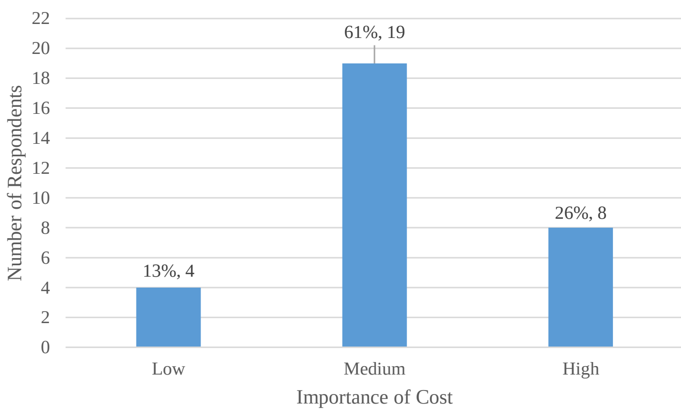


Figure 46. Importance of Cost – Total Responses

Number and percentage of responses, sorted by responding organization, are shown in Figure 47. Four out of 31 respondents (13 percent) ranked cost as low importance, one of which was a fabricator and three of which were state DOTs. Thirteen state DOTs (65 percent) ranked cost as medium importance. All consultants (five respondents) ranked cost as medium importance and all installers (three respondents) ranked cost as high importance.

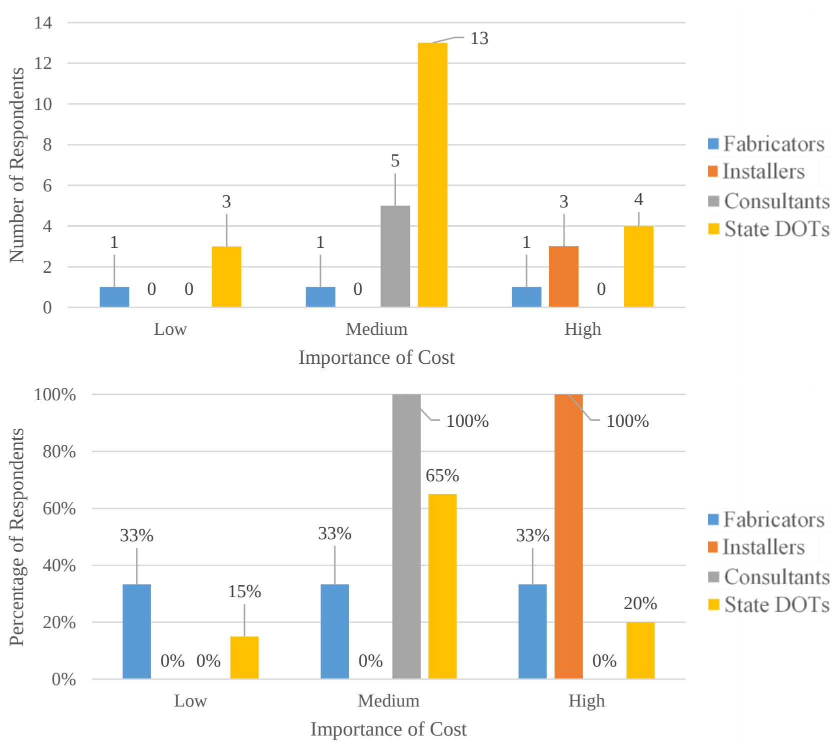


Figure 47. Importance of Cost – Responses by Organization

4.4.2 Question 2

Respondents were asked whether they would be willing to accommodate higher costs for portable barriers if durability and life cycle were to increase, as shown in Figure 48. In total, 26 respondents (84 percent) responded yes. Four respondents (13 percent), two installers and two state DOTs said they were not willing to accommodate a new higher cost portable barrier.

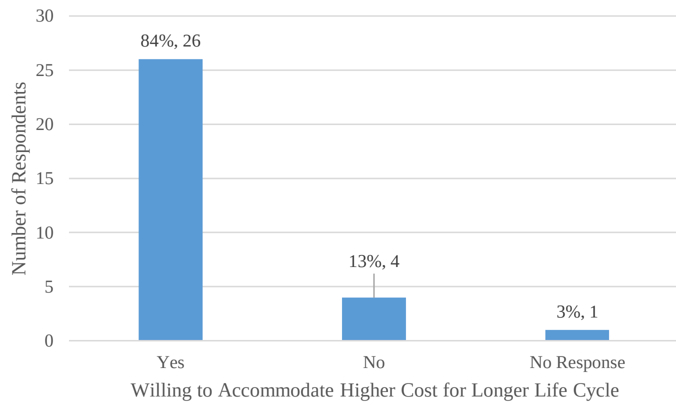


Figure 48. Willingness to Accommodate Higher Cost – Total Responses

Three fabricators (100 percent), one installer (33 percent), four consultants (80 percent), and eighteen state DOTs (90 percent) were willing to accommodate a higher cost barrier while two installers (67 percent) and two state DOTs (ten percent) were not willing to accommodate a higher cost barrier, as shown in Figure 49. Ultimately, installers will be affected by the increased cost more than fabricators, consultants, and state DOTs.

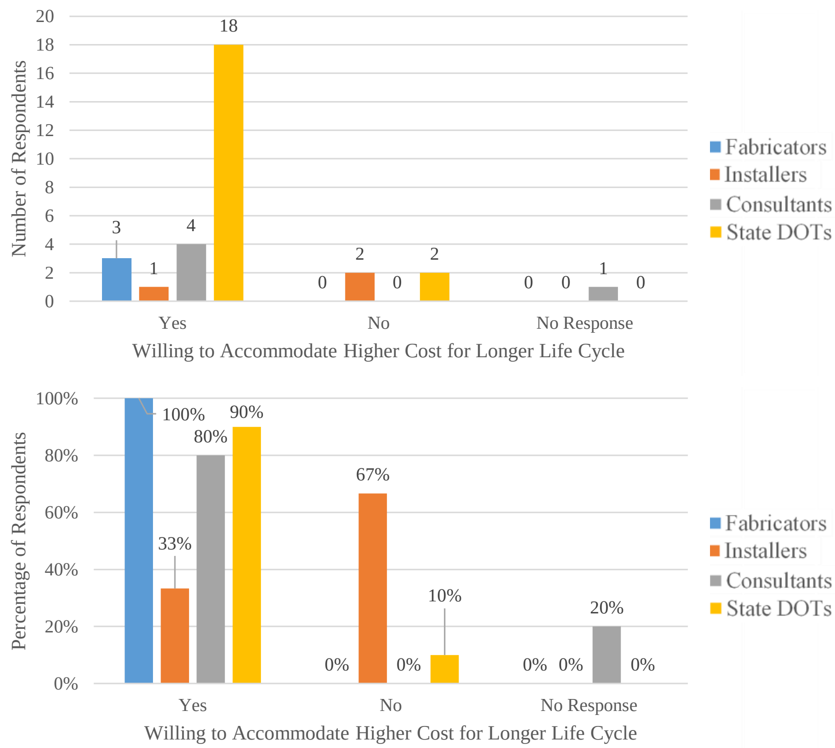


Figure 49. Willingness to Accommodate Higher Cost – Responses by Organization

4.4.3 Question 3

Question no. 3 inquired about acceptable cost per linear foot of a new portable barrier with a service life longer than twenty years, given that the current cost is approximately $48 to $80 per linear foot and current life cycle is approximately five to ten years. Acceptable costs were grouped in four ranges of $50 increments. A total of 16 respondents (52 percent) were willing to pay up to $100 per linear foot for a new portable barrier, as shown in Figure 50. Nine respondents (29 percent) were willing to pay between $101 and $200 per linear foot.

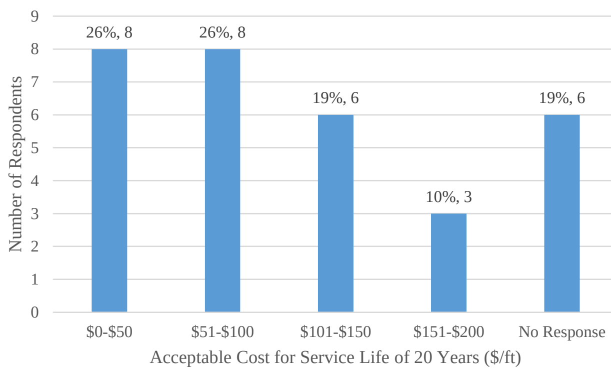


Figure 50. Acceptable Cost for 20 Year Service Life – Total Responses

All installers (three, 100 percent) were willing to pay a similar or slightly increased cost for new portable barriers. State DOTs responded with a relatively even distribution for each price range, with between 15 and 25 percent responding in each range. Responses for fabricators, installers, consultants, and state DOTs are shown in Figure 51.

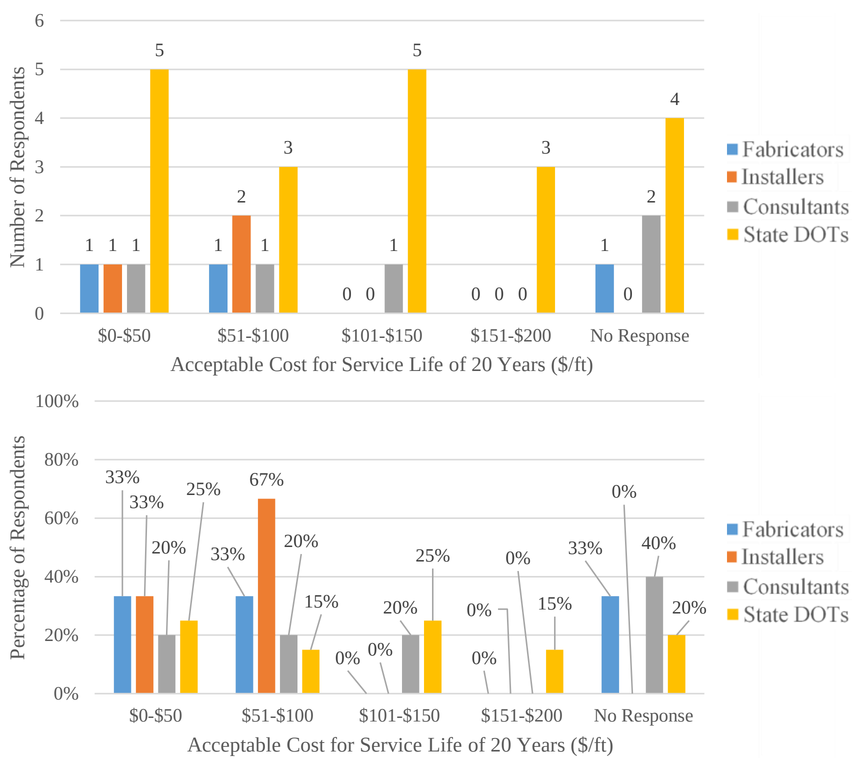


Figure 51. Acceptable Cost for 20 Year Service Life – Responses by Organization

4.4.4 Question 4

After a vehicle impact under MASH TL-3 test designation no. 3-11 impacted conditions, many portable barrier segments must be replaced due to damage. Question no. 4 asked respondents for an acceptable cost for barrier segments strong enough to withstand TL-3 impacts and be reusable afterward. Costs were grouped in $50 ranges, as shown in Figure 52. A total of 16 respondents (52 percent) were willing to pay up to $100 per linear foot for a new portable barrier. Eight respondents (26 percent) were willing to pay between $101 and $200 per linear foot.

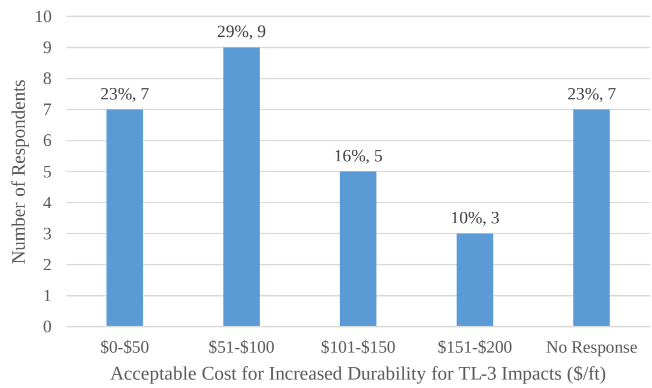


Figure 52. Acceptable Cost for Increased Durability – Total Responses

Again, installers were willing to pay a same or similar price as current portable barriers while state DOTs responded nearly equally for all price ranges, as shown in Figure 53. Fabricators responded with $0 to $50, $101 to $150, and no response. Three consultants (60 percent) noted costs between $51 and $150 per linear foot were acceptable, while the remaining two (40 percent) did not respond.

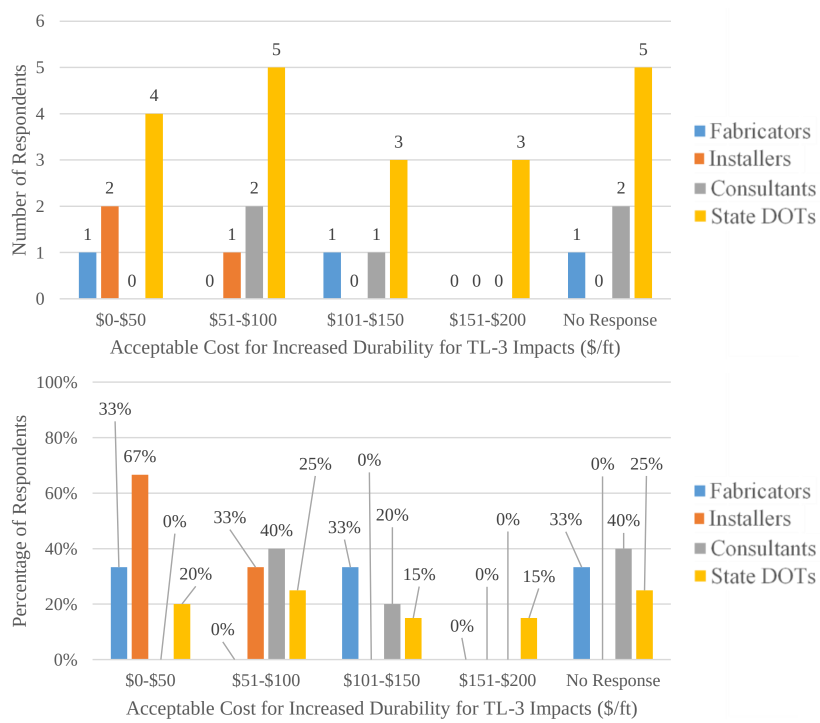


Figure 53. Acceptable Cost for Increased Durability – Responses by Organization

4.4.5 Question 5

Respondents were asked to rank concrete, steel, or plastic material for the barrier in terms of preference most, middle, or least preferred. In total, concrete was most preferred by 23 respondents (74 percent), steel was middle preferred by 20 respondents (65 percent), and plastic was least preferred by 23 respondents (74 percent), as shown in Figure 54.

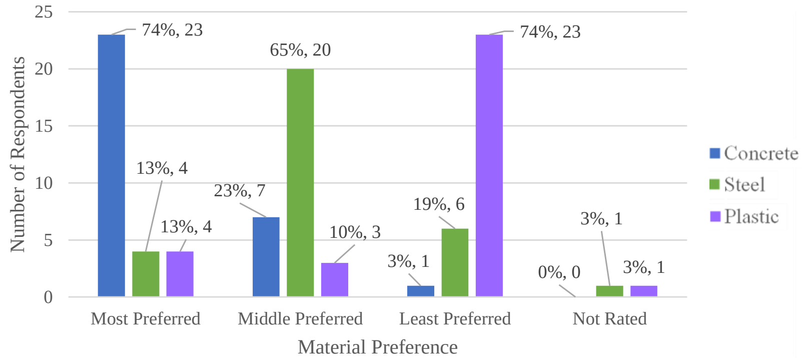


Figure 54. Material Preference – Total Responses

Three fabricators (100 percent), three installers (100 percent), three consultants (60 percent), and 14 state DOTs (70 percent) most preferred concrete, as shown in Figure 55. Steel was the middle preference for three fabricators (100 percent), two installers (67 percent), two consultants (40 percent), and 13 state DOTs (65 percent), as shown in Figure 56. Three fabricators (100 percent), two installers (67 percent), two consultants (40 percent), and 16 state DOTs (80 percent) least preferred plastic, as shown in Figure 57.

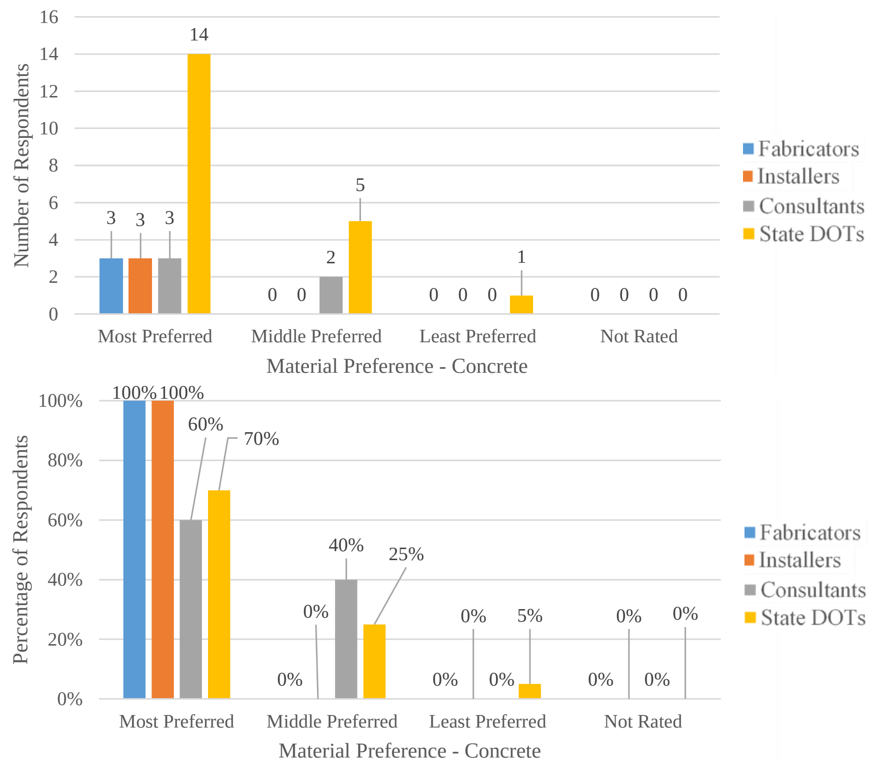


Figure 55. Material Preference (Concrete) – Responses by Organization

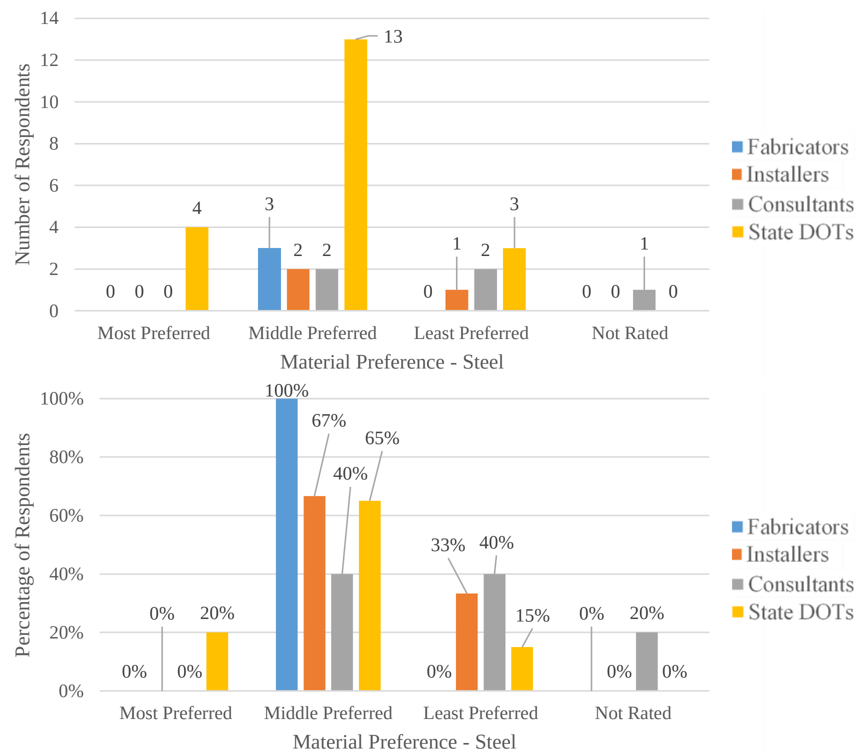


Figure 56. Material Preference (Steel) – Responses by Organization

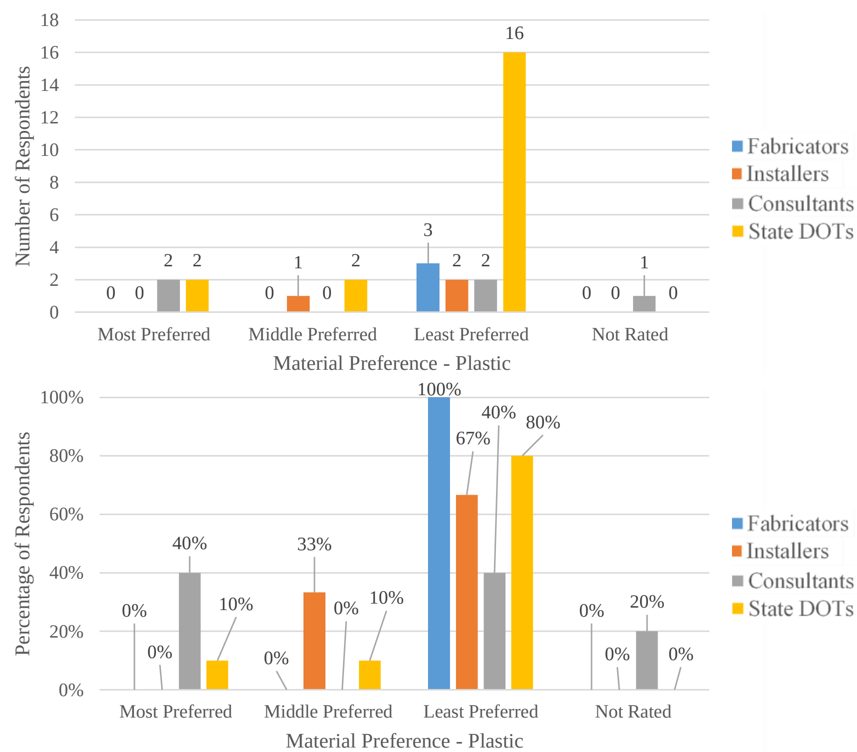


Figure 57. Material Preference (Plastic) – Responses by Organization

4.4.6 Question 6

Alternative concretes, such as those incorporating polymers or various types of fibers, feature improved strength and performance characteristics which may increase toughness and reduce damage. Respondents were asked if alternative concretes should be considered for the new portable barrier design, as shown in Figure 58. Twenty-eight respondents (90 percent) said yes, two respondents (six percent) said no, and one respondent (three percent) did not respond.

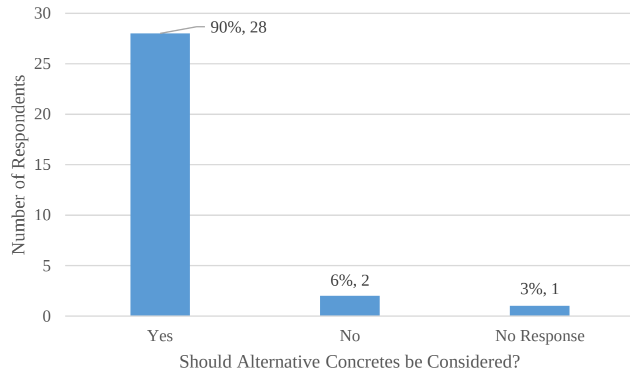


Figure 58. Alternative Concretes – Total Responses

Three fabricators (100 percent), three installers (100 percent), and five consultants (100 percent), and 17 state DOTs (85 percent) responded yes, as shown in Figure 59. The remaining three responses were from state DOTs, with two (ten percent) responding no and one (five percent) not giving a response.

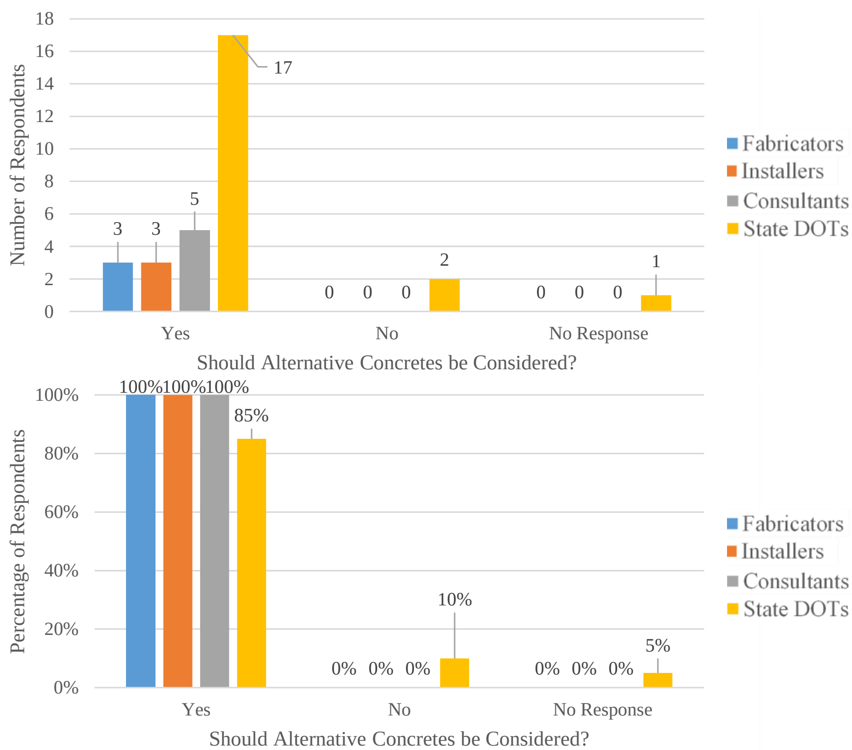


Figure 59. Alternative Concretes – Responses by Organization

4.4.7 Question 7

Respondents were asked if steel and plastic barriers should be ballasted to increase barrier mass and inertial resistance, as shown in Figure 60. In total, 22 respondents (71 percent) said yes, eight respondents (26 percent) said no, and one respondent (three percent) did not respond.

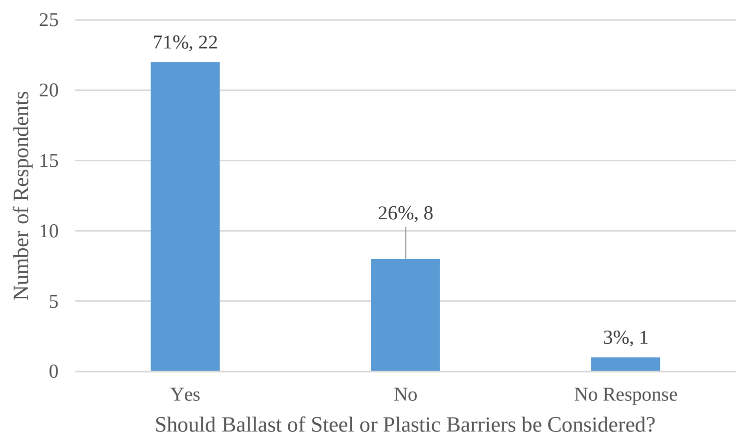


Figure 60. Ballast Steel or Plastic Barriers – Total Responses

Responses by organization are shown in Figure 61. Two fabricators (67 percent), two installers (67 percent), four consultants (80 percent), and 14 state DOTs (70 percent) responded yes. The remaining one fabricator (33 percent), one installer (33 percent), and one consultant (20 percent) responded no. Five state DOTs (25 percent) responded no and one state DOT (five percent) did not respond.

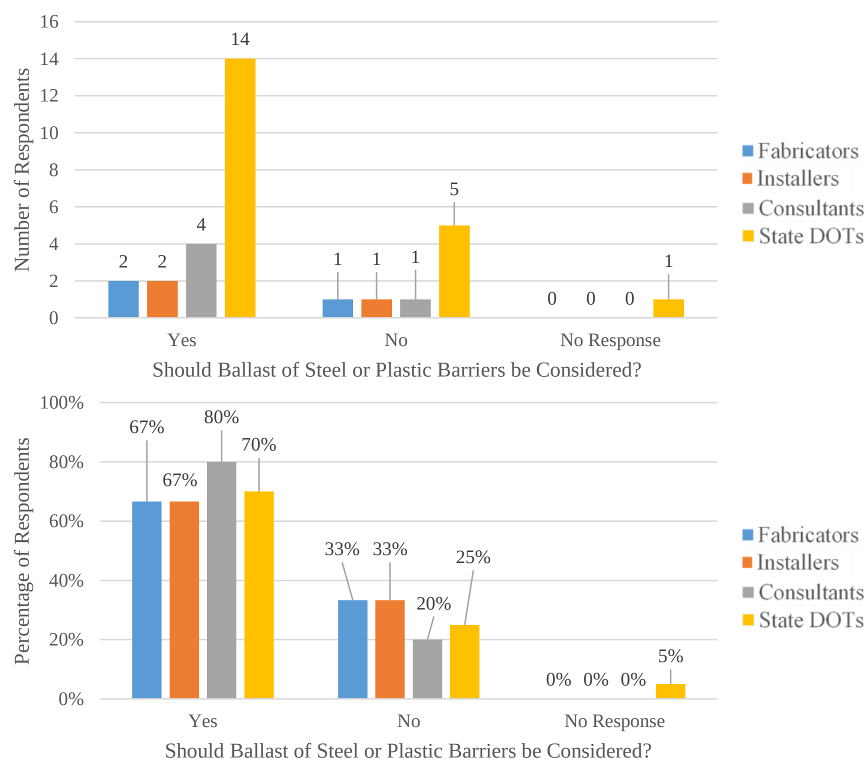


Figure 61. Ballast Steel or Plastic Barriers – Responses by Organization

4.4.8 Question 8

Question no. 8 asked for respondents' preference for steel barrier designs: increased durability, reusability, and extended life cycle for a higher initial cost; or reduced durability and shorter life cycle for a lower initial cost. Eighteen respondents (58 percent) said higher initial cost and increased durability, ten respondents (32 percent) said lower initial cost and reduced durability, and three respondents (ten percent) did not respond, as shown in Figure 62.

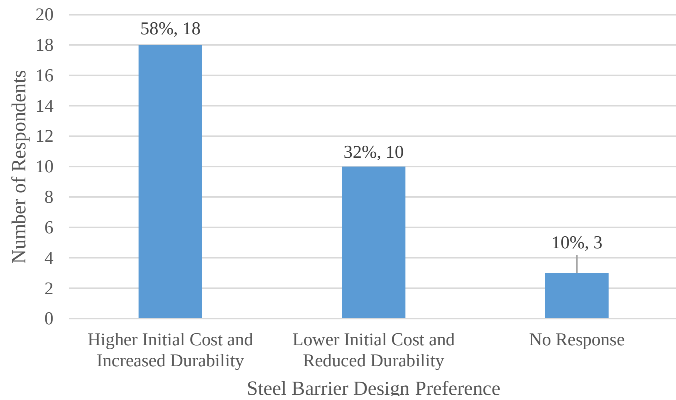


Figure 62. Steel Barrier Design Preference – Total Responses

Overall, a higher percentage of fabricators and state DOTs preferred a higher initial cost and increased durability barrier while a higher percentage of installers and consultants preferred a lower initial cost and reduced durability barrier, as shown in Figure 63. One fabricator (33 percent), one consultant (20 percent), and one state DOT (five percent) did not respond.

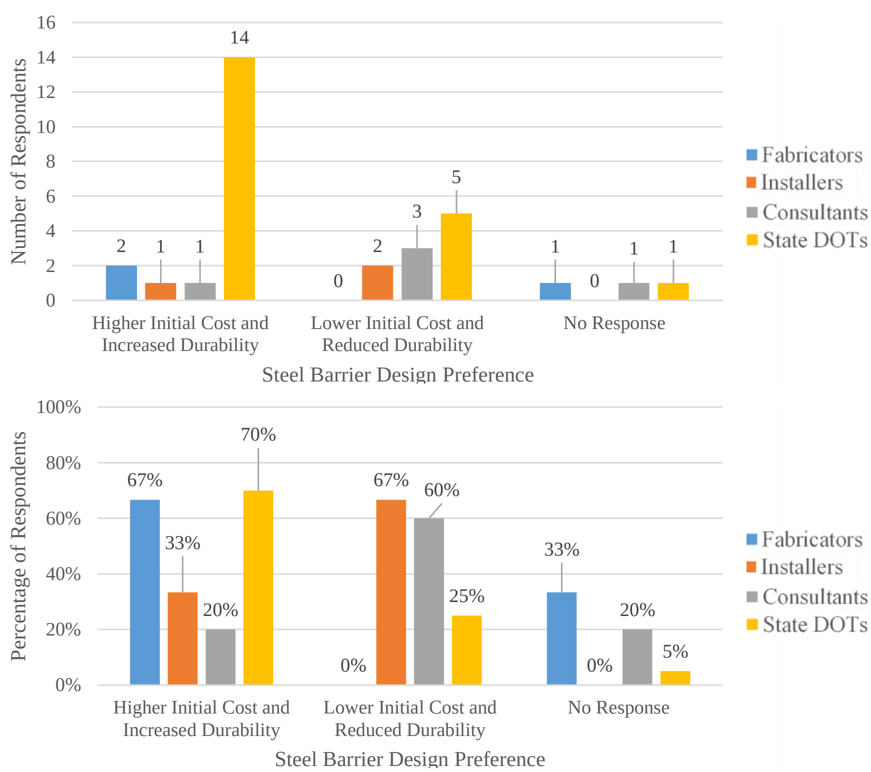


Figure 63. Steel Barrier Design Preference – Responses by Organization

4.4.9 Question 9

Respondents were asked to rank the importance of portable barrier durability as high, medium, or low during work zone operations, as shown in Figure 64. A total of 28 respondents (90 percent) ranked work zone durability as medium or high importance. Two respondents (six percent) responded with low importance.

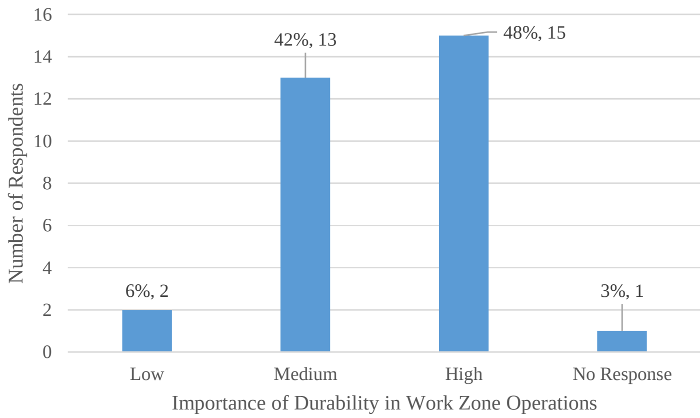


Figure 64. Importance of Durability in Work Zone Operations – Total Responses

Survey responses sorted by responding organization are shown in Figure 65. All fabricators (three, 100 percent) ranked the work zone durability as low or medium importance. All installers (three, 100 percent) and consultants (five, 100 percent) ranked work zone durability as medium or high importance. One state DOT (five percent) did not respond.

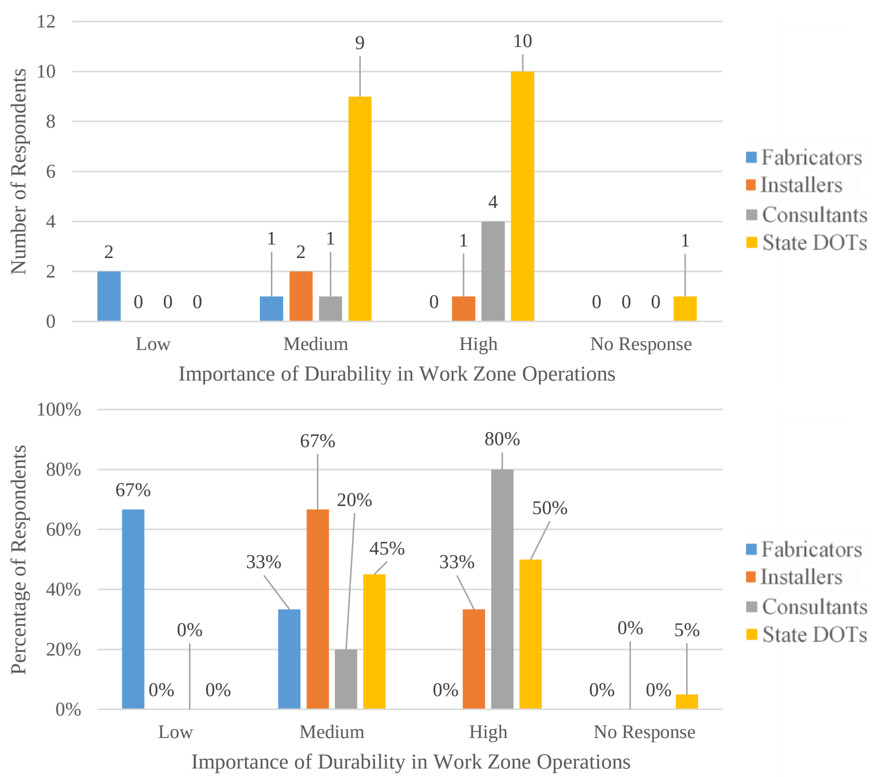


Figure 65. Importance of Durability in Work Zone Operations – Responses by Organization

4.4.10 Question 10

Respondents were asked to rank importance of portable barrier durability during transport as low, medium, or high, as shown in Figure 66. A total of 27 respondents (87 percent) ranked durability during transport as medium or high importance. Three respondents (ten percent) ranked importance as low. One respondent (three percent) did not respond.

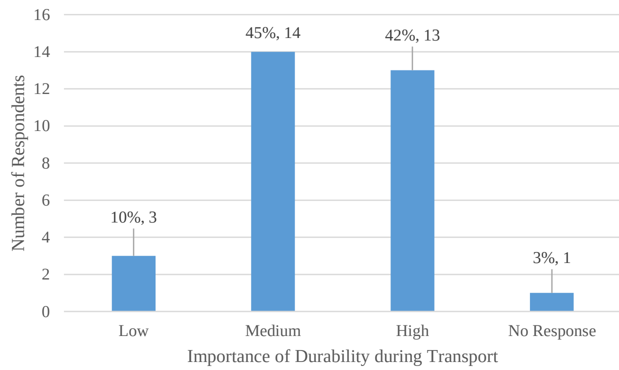


Figure 66. Importance of Durability during Transport – Total Responses

The three responding fabricators ranked importance of durability during transport as low (33 percent), medium (33 percent), and high (33 percent), as shown in Figure 67. One installer (33 percent) responded low importance and two installers (67 percent) responded medium importance. For consultants, one responded low (20 percent), two responded medium (40 percent), and two responded high (40 percent). Nine state DOTs (45 percent) responded with medium importance and ten (50 percent) responded with high importance. One state DOT (five percent) did not respond.

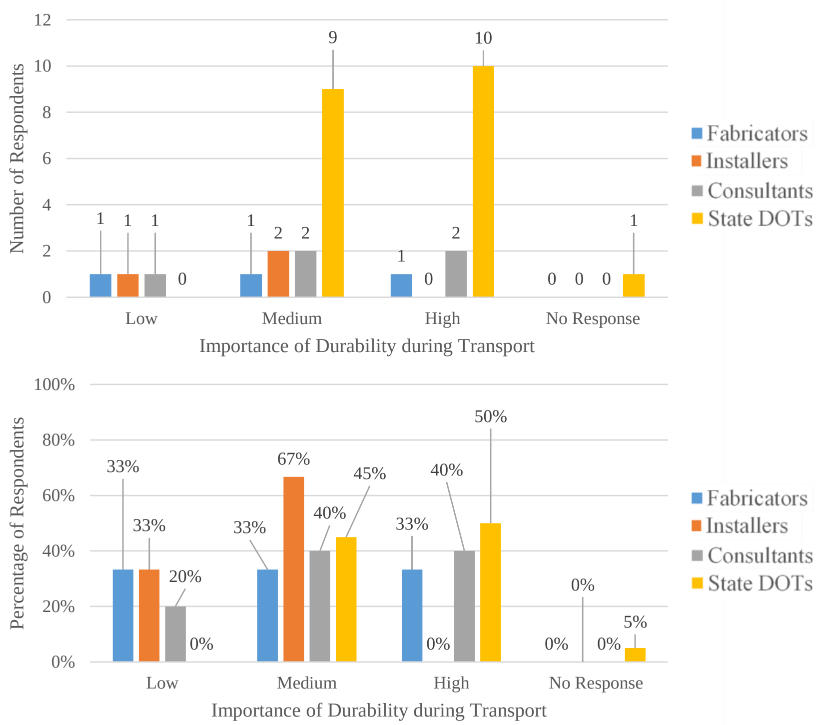


Figure 67. Importance of Durability during Transport – Responses by Organization

4.4.11 Question 11

Respondents were asked to rank the importance of durability during portable barrier installation as low, medium, or high, as shown in Figure 68. A total of 28 respondents (90 percent) ranked installation durability as medium or high importance. Two respondents (six percent) ranked it as low importance and one respondent (three percent) did not respond.

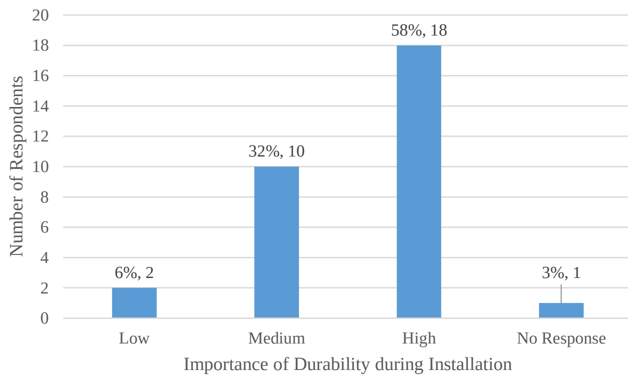


Figure 68. Importance of Durability during Installation – Total Responses

Fabricators responded with a low (one, 33 percent), medium (one, 33 percent), and high (one, 33 percent) rank for installation durability, as shown in Figure 69. All installers (three, 100 percent) ranked installation durability as high importance. Consultants ranked installation durability as either medium (two, 40 percent) or high (three, 60 percent). Majority of state DOTs responded with medium (seven, 35 percent) or high (eleven, 55 percent) importance. The two remaining state DOTs responded with low (one, five percent) and no response (one, five percent).

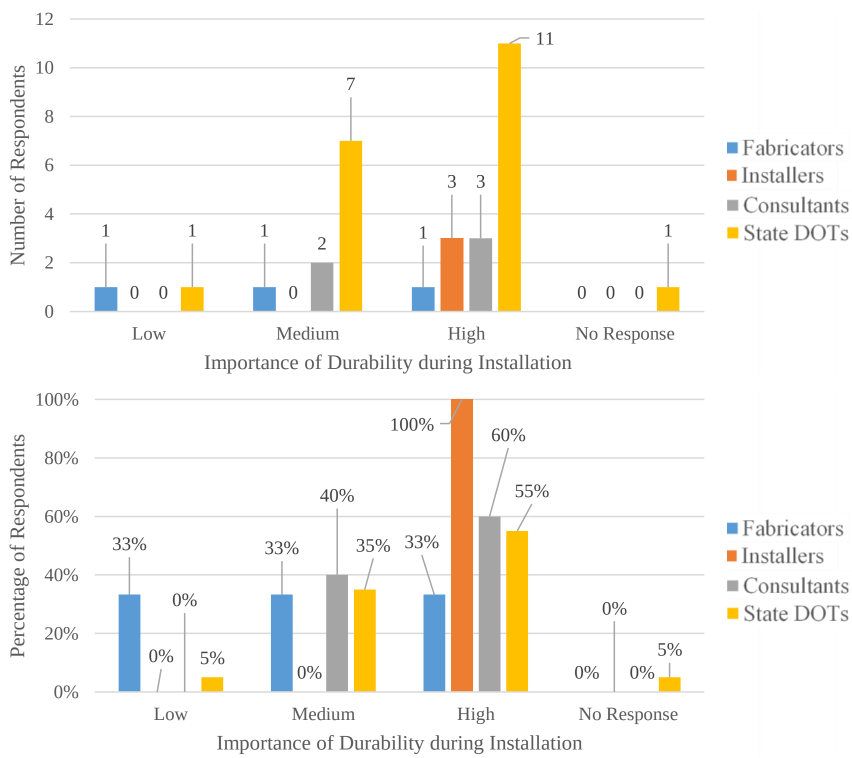


Figure 69. Importance of Durability during Installation – Responses by Organization

4.4.12 Question 12

Respondents were asked to rank the importance of transportability, including ease of shipping, lifting, positioning, and lifting attachments, as low, medium, or high shown in Figure 70. Majority of respondents, 22 (71 percent), responded with high importance. Another eight respondents (26 percent) responded with medium importance. One respondent (three percent) did not respond.

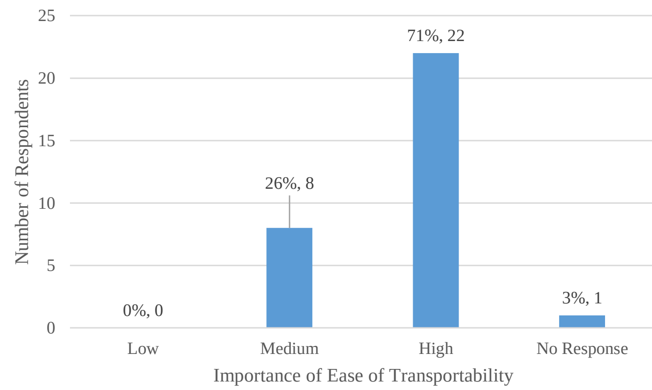


Figure 70. Importance of Ease of Transportability – Total Responses

No responding organizations ranked ease of transportability as low importance, as shown in Figure 71. All fabricators (three, 100 percent) and consultants (five, 100 percent) ranked ease of transportability as medium or high. Three installers (100 percent) responded with high importance. A total of 14 state DOTs (70 percent) responded with high importance, five (25 percent) responded with medium, and one (five percent) did not respond.

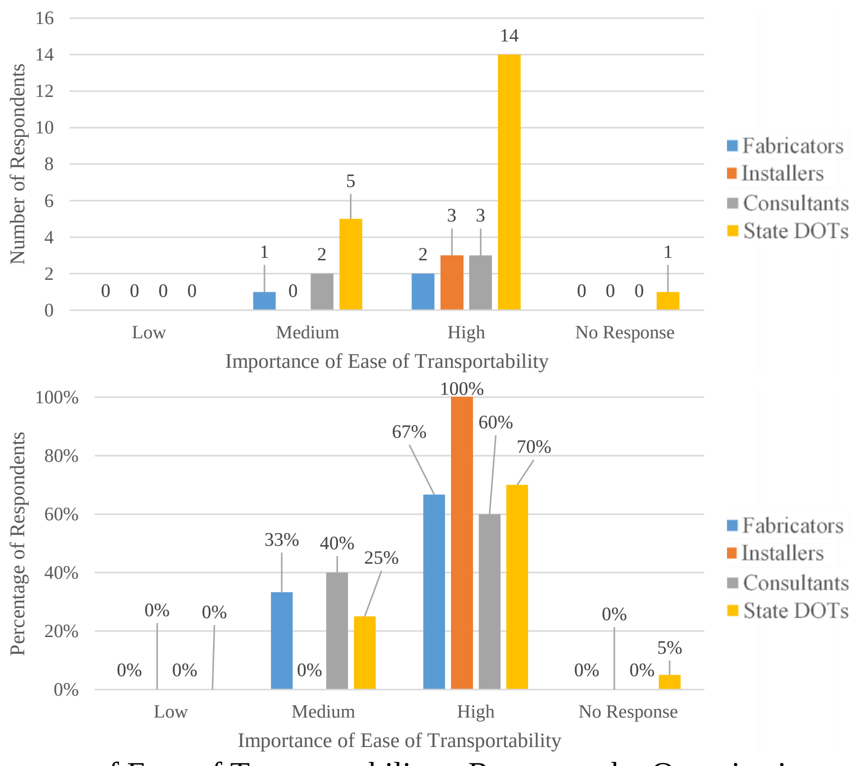


Figure 71. Importance of Ease of Transportability – Responses by Organization

4.4.13 Question 13

Respondents were asked to note the maximum allowable weight for a new portable barrier design based on available installation equipment. Barrier mass ranged between 5,000 lb to 10,000 lb and responses spanned the entire mass range, as shown in Figure 72. Five respondents (16 percent) did not respond. Of the 26 responses, 14 (54 percent) requested barriers no greater than 7,000 lb.

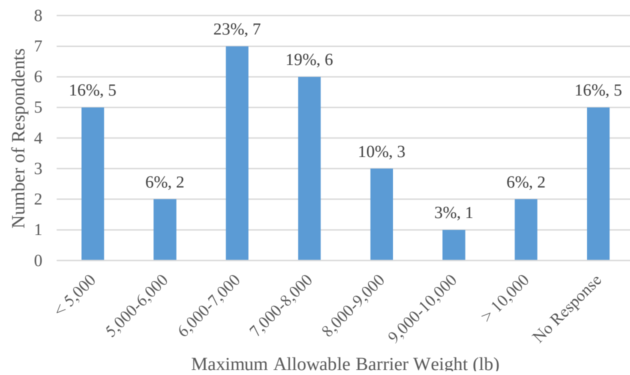


Figure 72. Maximum Allowable Barrier Weight – Total Responses

Responses by organization are shown in Figure 73. One fabricator (33 percent) did not respond, and the remaining two (67 percent) responded with 9,000 lb or greater. All installers (three, 100 percent) requested barriers weighing 7,000 lb or less. Consultants responded with weights ranging between less than 5,000 lb and greater than 10,000 lb. Four state DOTs (20 percent) did not respond. The remaining 16 state DOTs responded with weights between less than 5,000 lb and 9,000 lb.

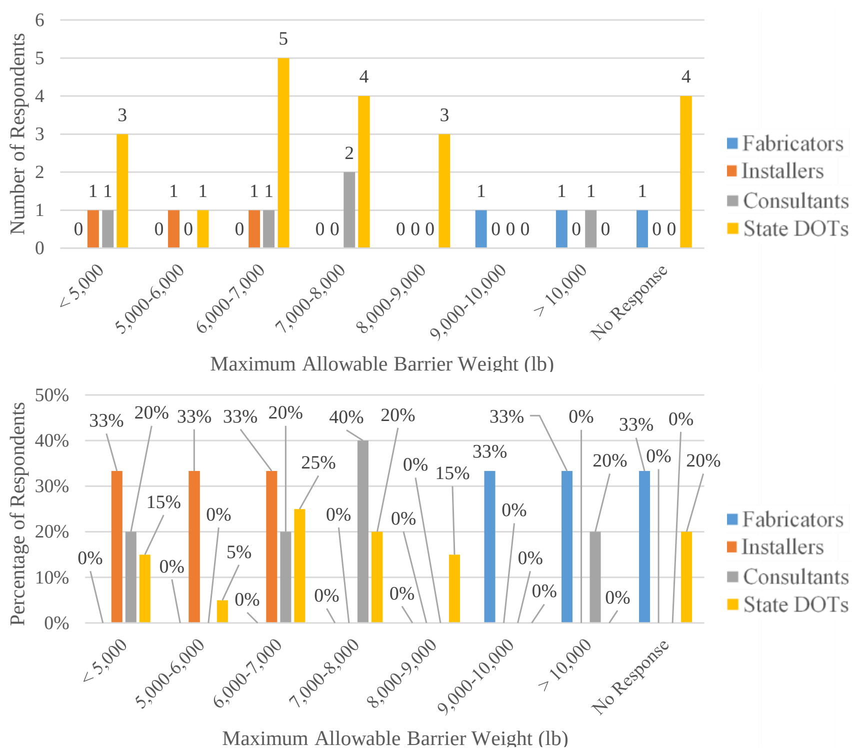


Figure 73. Maximum Allowable Barrier Weight – Responses by Organization

4.4.14 Question 14

Question no. 14 asked respondents to note the preferred barrier segment length, between 10 and 20 ft, in 2-ft increments, as shown in Figure 74. Two respondents (six percent) did not respond. Of the 29 respondents who gave an answer, 14 (48 percent) responded with barrier lengths of 12 ft or less. The remaining 15 respondents (52 percent) noted barrier lengths between 12 and 20 ft.

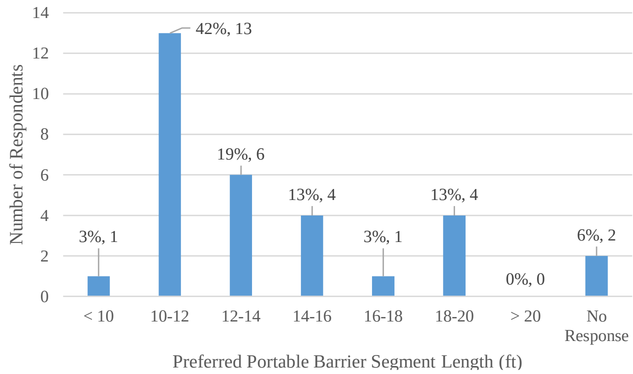


Figure 74. Preferred Portable Barrier Segment Length – Total Responses

Responses to barrier segment length are shown in Figure 75. One fabricator (33 percent) did not respond, and the remaining two fabricators (67 percent) responded with 18 to 20 ft. All installers (three, 100 percent) requested barrier lengths between 12 and 16 ft. All consultants (five, 100 percent) responded with lengths less than 10 ft and up to 16 ft. One state DOT (five percent) did not respond and the remaining 19 (95 percent) responded between 10 and 20 ft, with majority requesting 10- to 12-ft segment lengths.

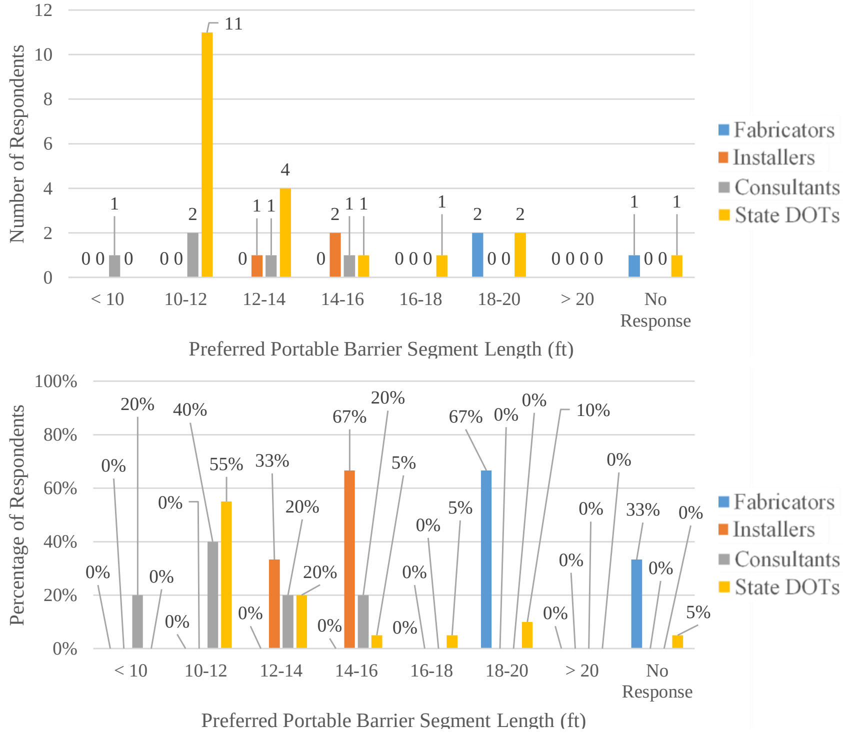


Figure 75. Preferred Portable Barrier Segment Length – Responses by Organization

4.4.15 Question 15

Question no. 15 asked the importance of being able to place barriers either horizontally or vertically without interference from adjacent barrier segments. A total of 28 respondents (90 percent) ranked this as either medium or high importance, as shown in Figure 76.

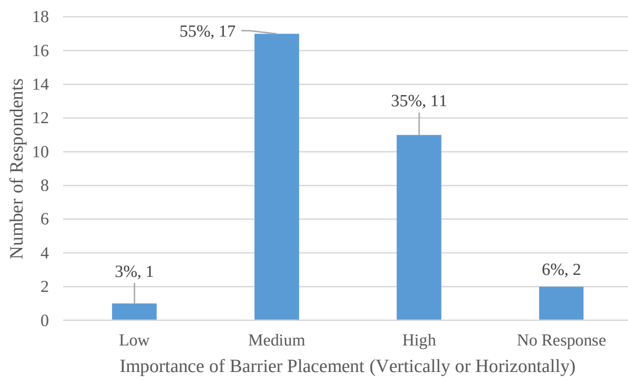


Figure 76. Importance of Barrier Placement – Total Responses

Responses to question no. 15 are shown in Figure 77, sorted by responding organization. One fabricator (33 percent) did not respond, one (33 percent) responded with medium importance, and one (33 percent) responded with high importance. All installers (three, 100 percent) responded with medium importance. Consultants ranked the importance as medium (two, 40 percent) and high (three, 60 percent). One state DOT (five percent) responded low, 11 (55 percent) responded medium, seven (35 percent) responded high, and one (five percent) did not respond.

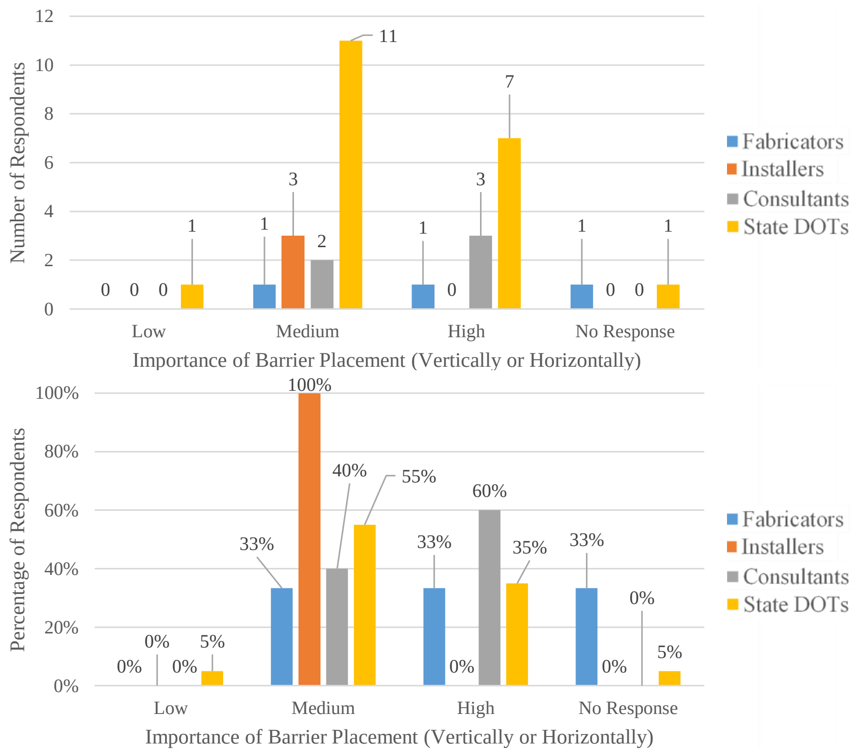


Figure 77. Importance of Barrier Placement – Responses by Organization

4.4.16 Question 16

The ease of barrier-to-barrier segment connection and elimination of tools was ranked in terms of importance: low, medium, or high, as shown in Figure 78. Twenty-six respondents (84 percent) responded with high importance, four (13 percent) responded with medium importance, and one (three percent) did not respond.

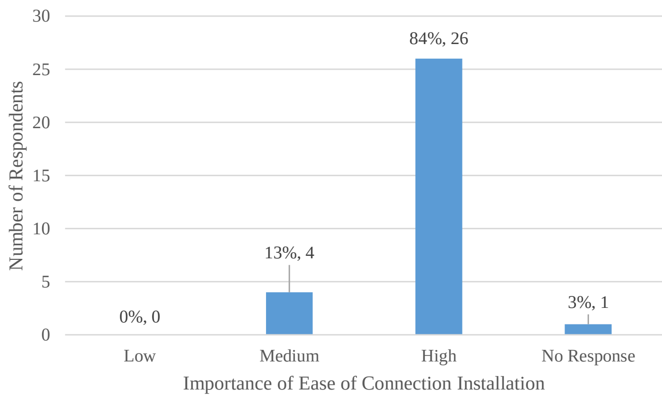


Figure 78. Importance of Ease of Connection Installation – Total Responses

All fabricators (three, 100 percent), installers (three, 100 percent), and consultants (five, 100 percent) ranked ease of connection as high importance, as shown in Figure 79. Fifteen state DOTs (75 percent) ranked ease of connection as high importance, four (20 percent) ranked as medium importance, and one (five percent) did not respond.

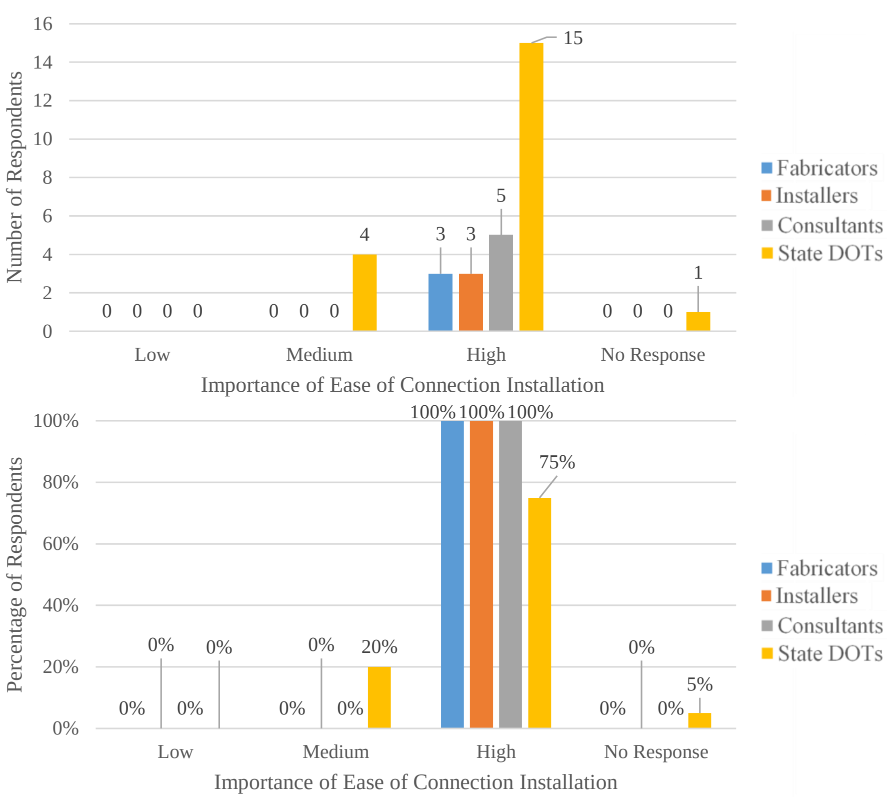


Figure 79. Importance of Ease of Connection Installation – Responses by Organization

4.4.17 Question 17

Question no. 17 asked the importance of the barrier's ability to accommodate horizontal and vertical curves, as shown in Figure 80. A total of 28 respondents (90 percent) ranked this as medium or high importance. Two respondents (six percent) responded with low importance and one (three percent) did not respond.

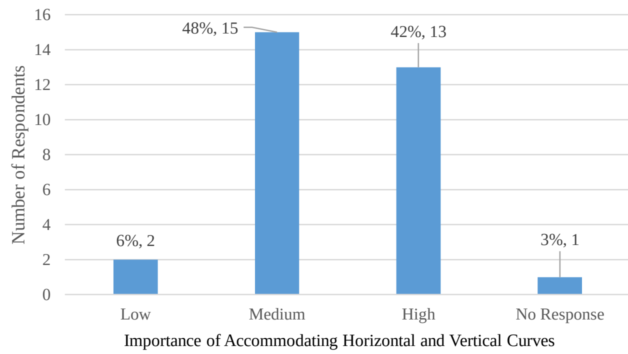


Figure 80. Importance of Barrier to Accommodate Curves – Total Responses

Results sorted by responding agency are shown in Figure 81. Three fabricators (100 percent) ranked the ability to accommodate curves as medium importance. One installer (33 percent) responded with medium importance and two installers (67 percent) responded with high. Similarly, two consultants (40 percent) responded with medium importance and three consultants (60 percent) responded with high importance. Seventeen state DOTs (85 percent) ranked importance as medium or high. Two state DOTs (ten percent) ranked importance as low and one (five percent) did not respond.

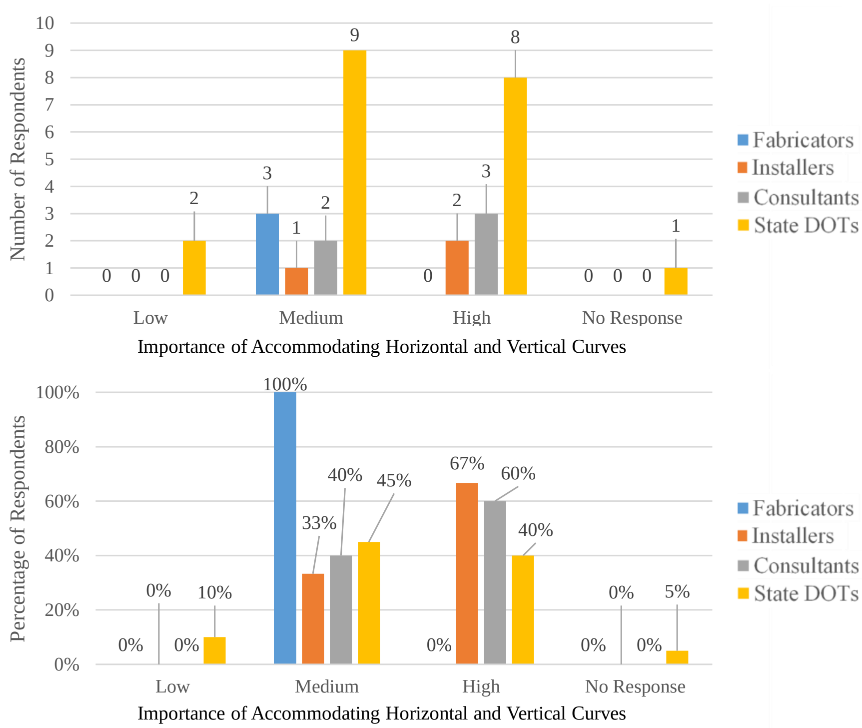


Figure 81. Importance of Barrier to Accommodate Curves – Responses by Organization

4.4.18 Question 18

Responders were asked to rank the importance of drainage in portable barriers as low, medium, or high, as shown in Figure 82. Three respondents (ten percent) ranked importance as low, twelve (39 percent) ranked medium, 15 (48 percent) ranked high, and one (three percent) did not respond. In total, 27 respondents (87 percent) ranked drainage as medium or high importance.

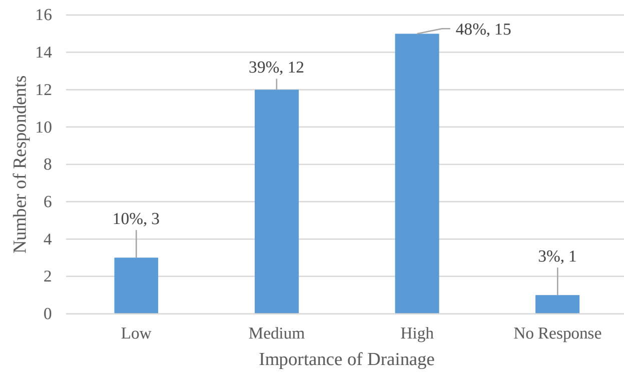


Figure 82. Importance of Drainage – Total Responses

One fabricator (33 percent) ranked importance as low, while the remaining two (67 percent) ranked high, as shown in Figure 83. Three installers (67 percent) ranked importance as medium and one (33 percent) ranked importance as high. One consultant (20 percent) responded low, one (20 percent) responded medium, and three (60 percent) responded high. One state DOT (five percent) did not respond and one (five percent) ranked the importance as low. The remaining state DOTs were split in half ranking the importance as medium or high importance (nine, 45 percent).

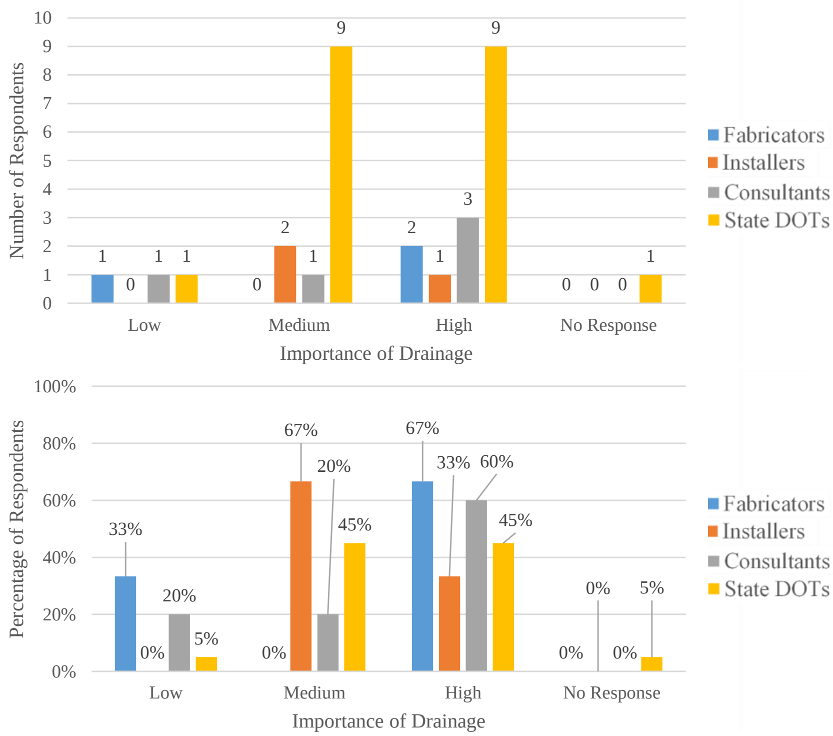


Figure 83. Importance of Drainage – Responses by Organization

4.4.19 Question 19

Respondents were asked to rank the importance of ease of inspection as low, medium, or high, as shown in Figure 84. Two respondents (six percent) gave no response, one (three percent) ranked importance as low, and the remaining 28 respondents (90 percent) ranked importance as medium or high.

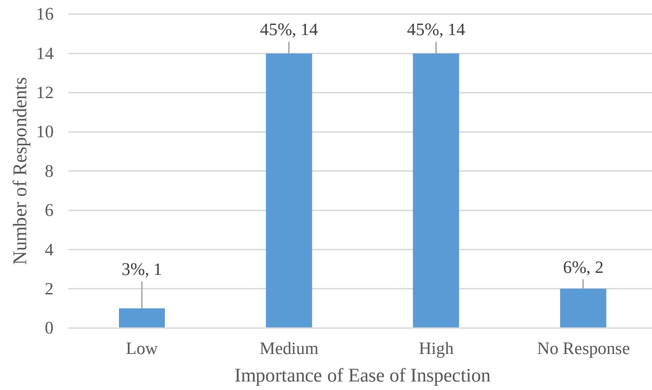


Figure 84. Importance of Ease of Inspection – Total Responses

Responses by responding organization are shown in Figure 85. Three fabricators (100 percent) ranked importance of ease of inspection as medium. One installer (33 percent) responded with low and two (67 percent) responded with medium. Three consultants (60 percent) ranked importance as medium and two (40 percent) ranked importance as high. Six state DOTs (30 percent) ranked importance as medium, 12 (60 percent) ranks as high, and two (ten percent) did not respond.

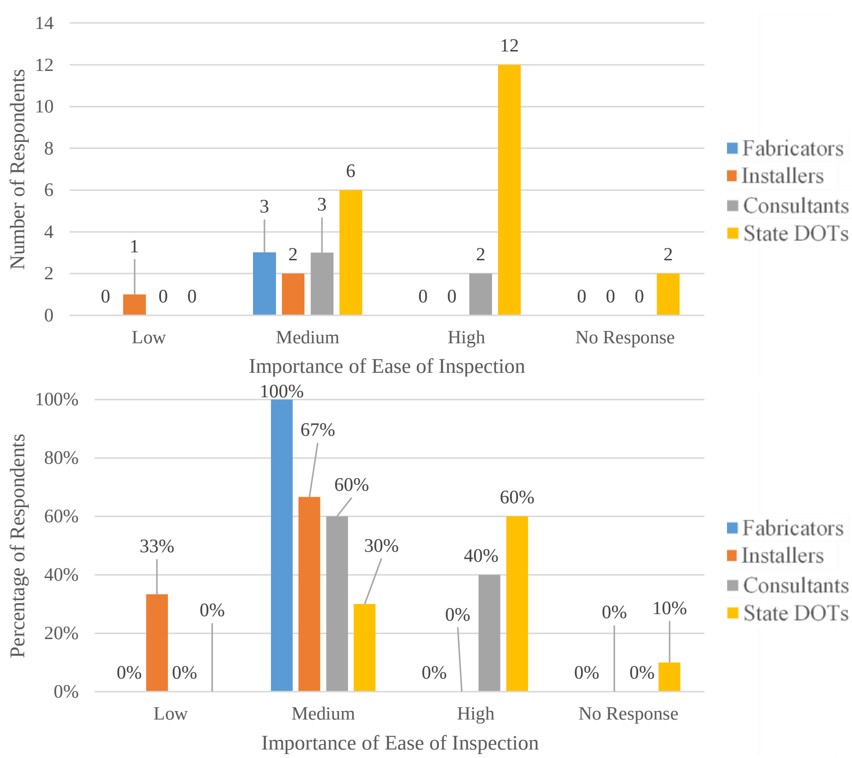


Figure 85. Importance of Ease of Inspection – Responses by Organization

4.4.20 Question 20

Regarding drainage, responders were asked to give dimensions in drainage slot length per barrier length, as shown in Figure 86. In total, 68 percent of respondents gave no response or a value greater than 1, which would result in drainage slots longer than the length of the barrier. Therefore, the applicable ten responses ranged between 0 and 0.5.

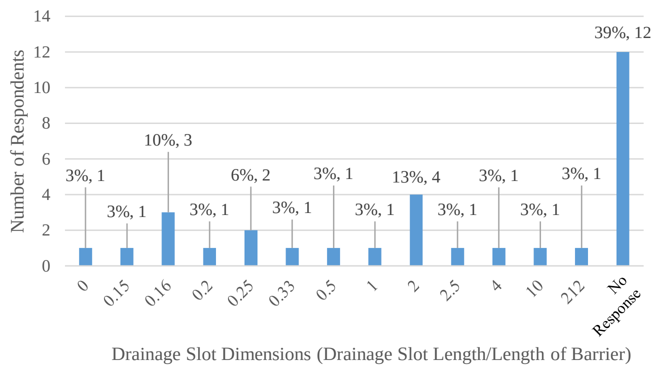


Figure 86. Drainage Slot Dimensions – Total Responses

Responses sorted by responding organization are shown in Figure 87. One fabricator (33 percent) responded with 0.16 and two (67 percent) responded with incorrect or no response. All installers either responded with 0 (one, 33 percent) or incorrect or no response (two, 67 percent). One consultant (20 percent) responded with 0.5 and the remaining four consultants (80 percent) gave incorrect or no response. Fourteen state DOTs (70 percent) gave incorrect or no response regarding drainage slot dimensions. The remaining six state DOTs (30 percent) gave values between 0.16 and 0.33.

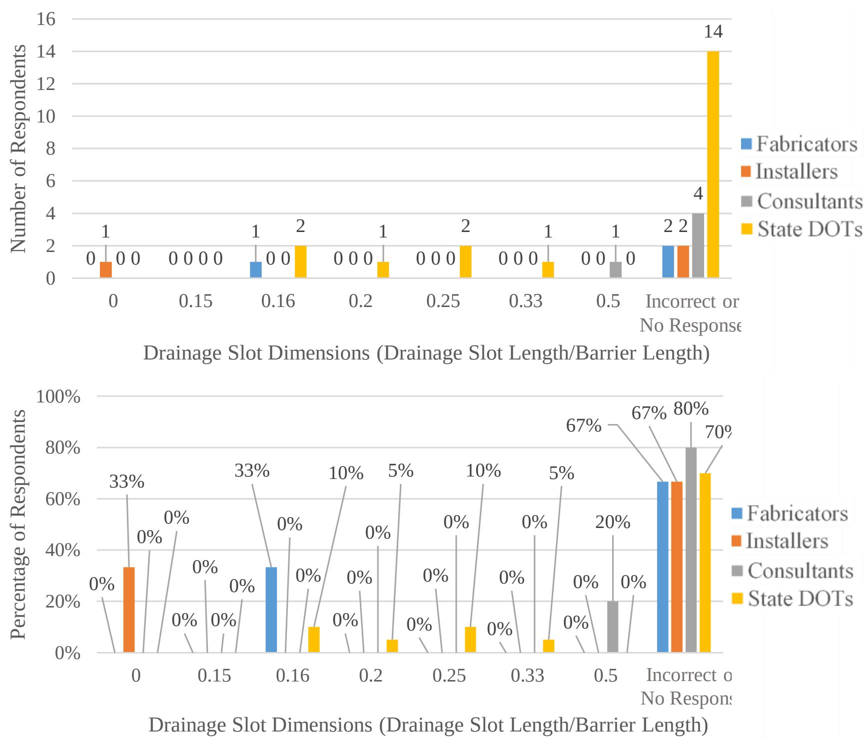


Figure 87. Drainage Slot Dimensions – Responses by Organization

4.4.21 Question 21

Respondents were asked the minimum horizontal radius of curvature required for their portable barrier installations, as shown in Figure 88. Twenty respondents (65 percent) did not give a response. The remaining 11 respondents (35 percent) gave values between 0 and 770 ft.

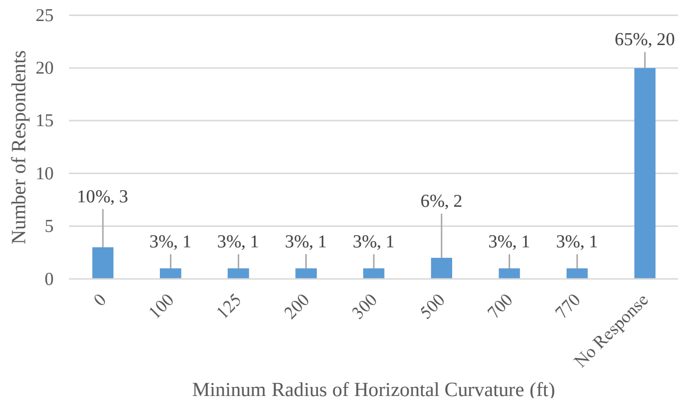


Figure 88. Minimum Radius of Horizontal Curvature – Total Responses

Responses by responding organization are shown in Figure 89. All fabricators (100 percent) gave no response. One installer (33 percent) responded with 0 ft and two (67 percent) did not respond. One consultant (20 percent) responded with 0 ft, one (20 percent) responded with 500 ft, and the remaining three (60 percent) did not respond. Twelve state DOTs (60 percent) did not respond and the remaining eight (40 percent) responded with radius of curvatures ranging between 0 and 770 ft.

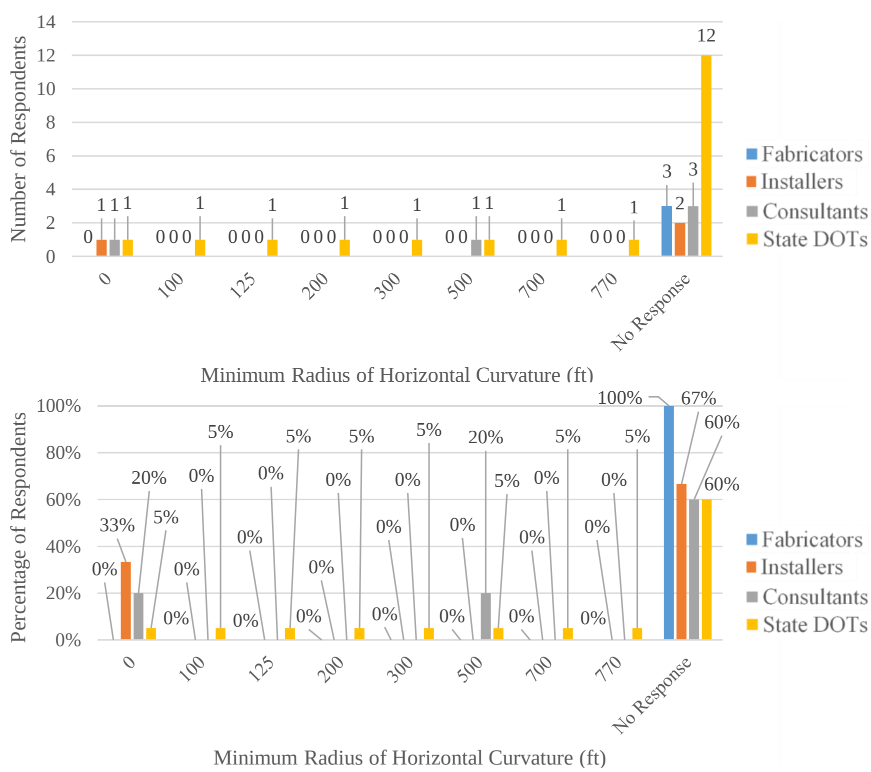


Figure 89. Minimum Radius of Horizontal Curvature – Responses by Organization

4.4.22 Question 22

All respondents were asked for a maximum flare rate value that they use when installing portable barriers in the field, as shown in Figure 90. Thirteen respondents (42 percent) gave no response. Two respondents (six percent) referenced the AASHTO Roadside Design Guide (RDG). The remaining 16 respondents (52 percent) gave flare rates between 4:1 and 18:1.

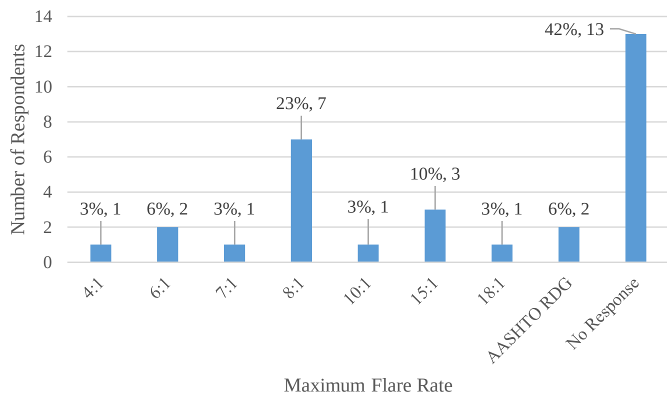


Figure 90. Maximum Flare Rate – Total Responses

Responses sorted by responding agency are shown in Figure 91. Three fabricators (100 percent) gave no response. Two installers (67 percent) did not respond, and one installer (33 percent) gave a flare rate of 6:1. Two consultants (40 percent) did not respond, one (20 percent) gave a flare rate of 8:1, one (20 percent) gave 15:1, and one (20 percent) gave 18:1. Six state DOTs (30 percent) responded with 8:1, six (30 percent) did not respond, and the remaining eight (40 percent) gave responses between 4:1 and 15:1.

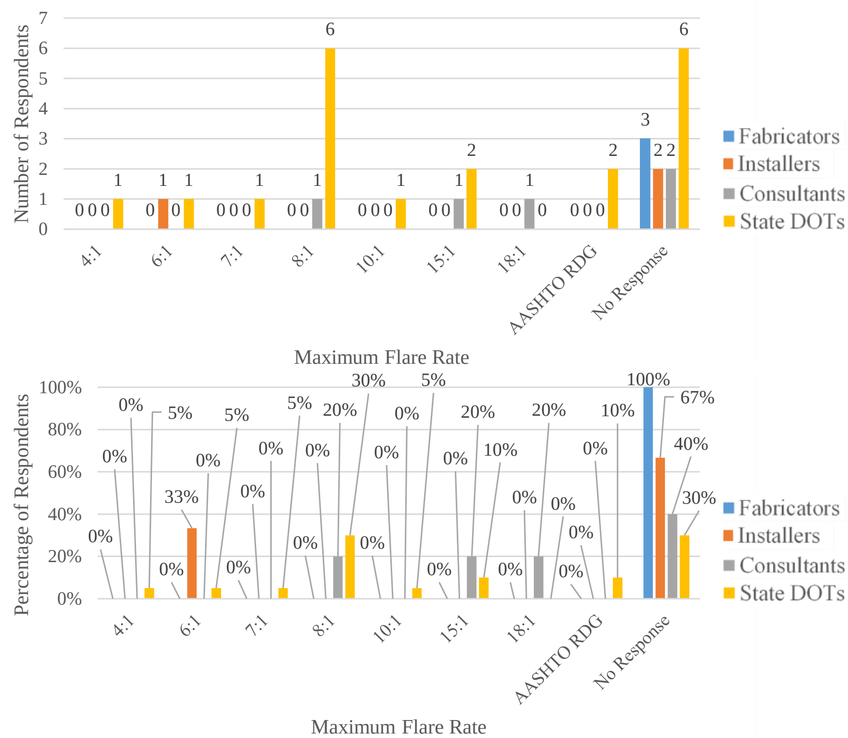


Figure 91. Maximum Flare Rate – Responses by Organization

4.4.23 Question 23

Question no. 23 asked respondents to give either a maximum vertical curvature in feet or a maximum percent grade. Total responses for maximum vertical curvature are shown in Figure 92 and maximum percent grade are shown in Figure 94.

Twenty-nine respondents (94 percent) did not give a maximum vertical curvature. One respondent (three percent) gave a value of 1,000 ft and one respondent (three percent) gave a value of 1,200 ft.

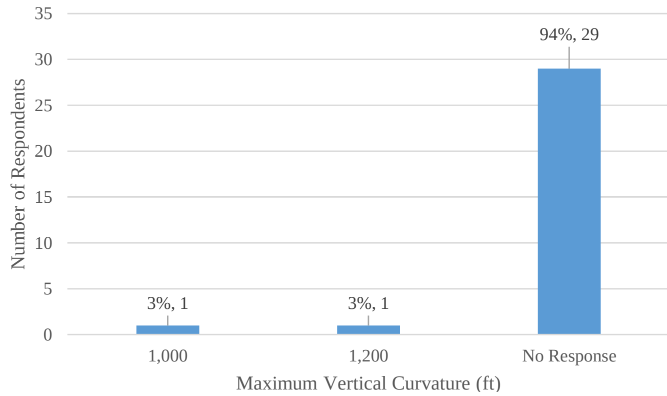


Figure 92. Maximum Vertical Curvature – Total Responses

No fabricators, installers, or consultants gave values for maximum vertical curvatures, as shown in Figure 93. Furthermore, 18 of the 20 state DOTs (90 percent) did not respond. Two state DOTs (ten percent) gave maximum vertical curvatures of 1,000 and 1,200 ft.

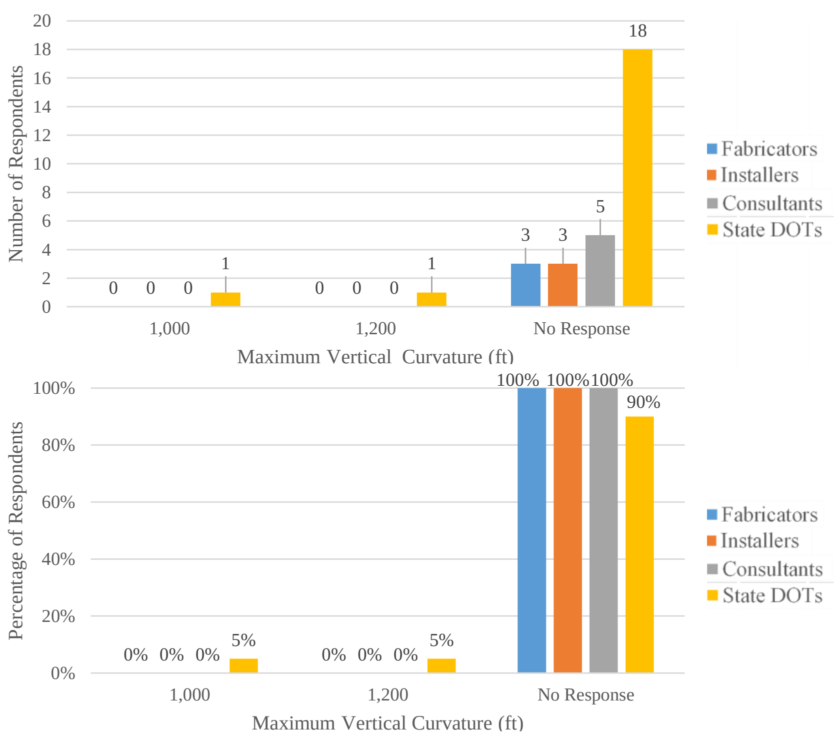


Figure 93. Maximum Vertical Curvature – Responses by Organization

Total responses for maximum percent grades are shown in Figure 94. Twenty-one respondents (68 percent) did not give a response. One respondent (three percent) said there is no maximum value. The remaining ten respondents (32 percent) gave values between 4 and 20 percent.

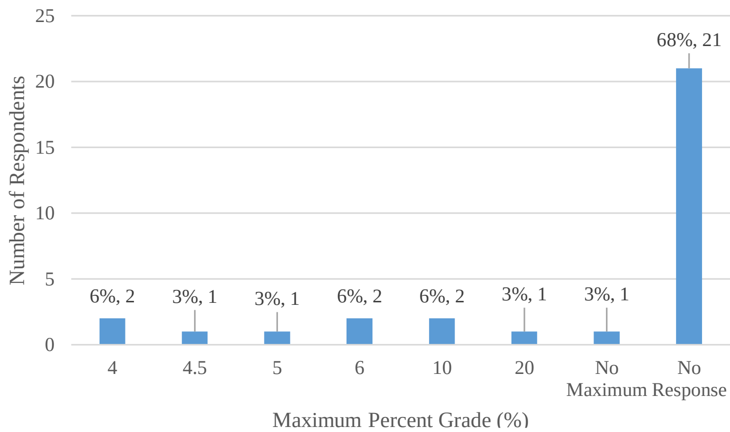


Figure 94. Maximum Percent Grade – Total Responses

No fabricators or installers gave a response for maximum percent grade, as shown in Figure 95. One consultant (20 percent) gave a value of 4.5 percent, one consultant (20 percent) gave 10 percent, one consultant (20 percent) gave 20 percent, and two consultants (40 percent) gave no response. Thirteen state DOTs (65 percent) gave no response, one (five percent) said there is no maximum value, and the remaining six (30 percent) gave values between 4 and 10 percent.

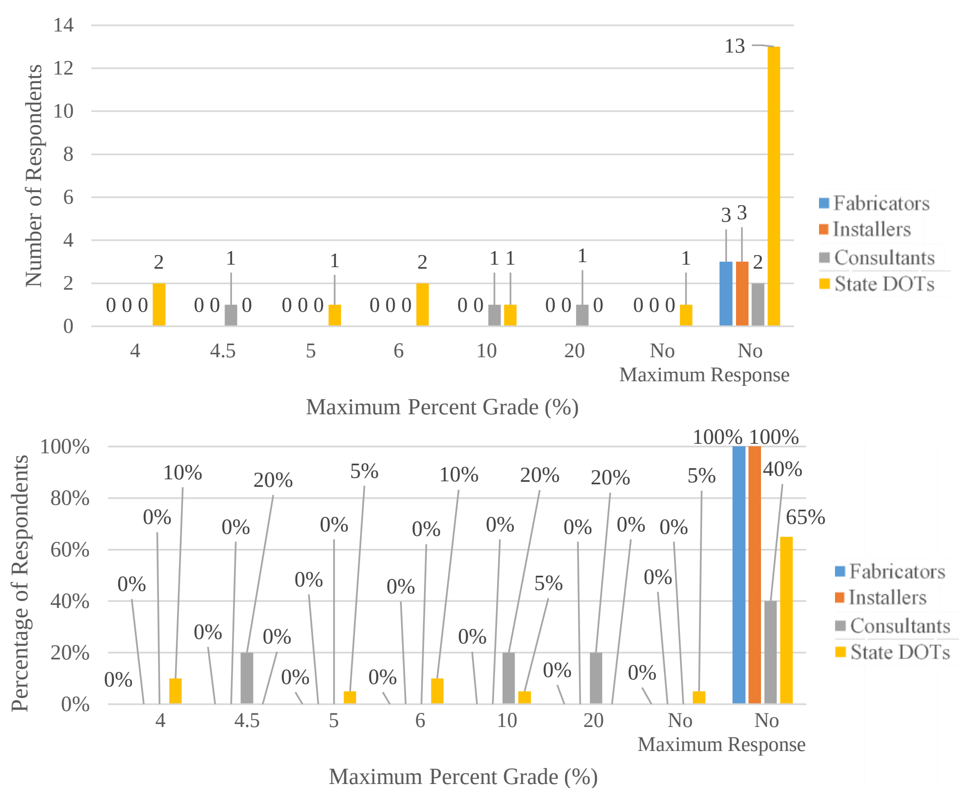


Figure 95. Maximum Percent Grade – Responses by Organization

4.4.24 Question 24

Respondents were asked the importance of the barrier withstanding MASH TL-3 impact loads with limited or minimal damage, as shown in Figure 96. Four respondents (13 percent) did not respond. Three respondents (ten percent) responded low, 11 (35 percent) responded medium, and 13 (42 percent) responded high. In total, 24 respondents (77 percent) ranked importance as high or medium.

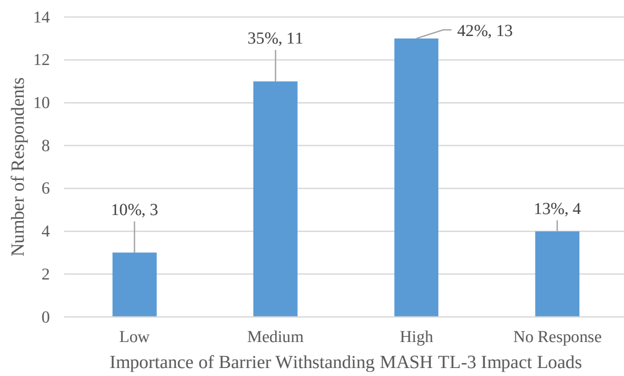


Figure 96. Importance of Barrier Withstanding MASH TL-3 Impact Loads – Total Responses

One fabricator (33 percent) responded with low, medium, and high importance each, as shown in Figure 97. One installer (33 percent) did not respond, and the remaining two (67 percent) responded with medium and high. Three consultants (60 percent) ranked importance as medium and two consultants (40 percent) ranked importance as high. Two state DOTs (ten percent) said low importance, six (30 percent) said medium, nine (45 percent) said high, and three (15 percent) did not respond.

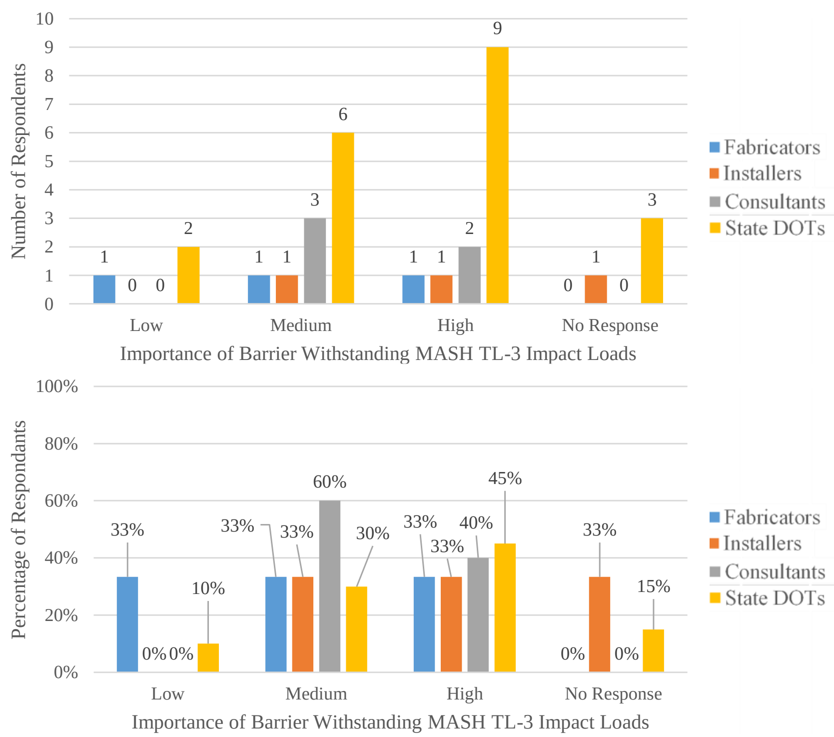


Figure 97. Importance of Withstanding MASH TL-3 Impact Loads – Responses by Organization

4.4.25 Question 25

Respondents were asked to rank the importance of improving vehicle stability by using a vertical or near-vertical barrier shape, as shown in Figure 98. Overall, 21 respondents (68 percent) ranked this as medium or high importance. Sixteen percent of respondents gave no response and five respondents (16 percent) ranked importance as low.

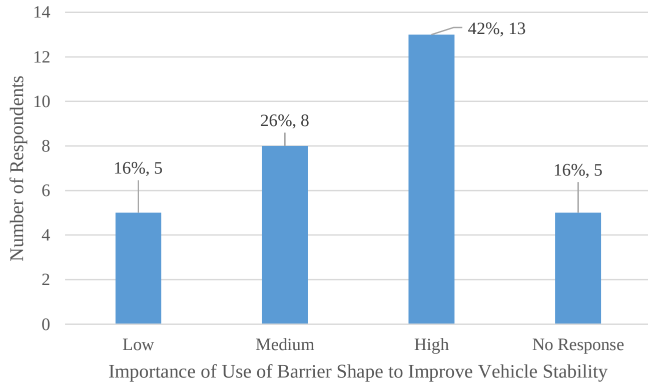


Figure 98. Importance of Use of Barrier Shape to Improve Vehicle Stability – Total Responses

The rank of importance of improving vehicle stability by responding organizations are shown in Figure 99. Two fabricators (67 percent) responded with high importance and one (33 percent) did not respond. Installers responded with low, medium, and no response, one (33 percent) for each. Consultants ranked vehicle stability importance as medium or high, with two respondents (40 percent) saying medium and three (60 percent) saying high. Four state DOTs (20 percent) responded low, five (25 percent) responded medium, eight (40 percent) responded high, and three (15 percent) did not respond.

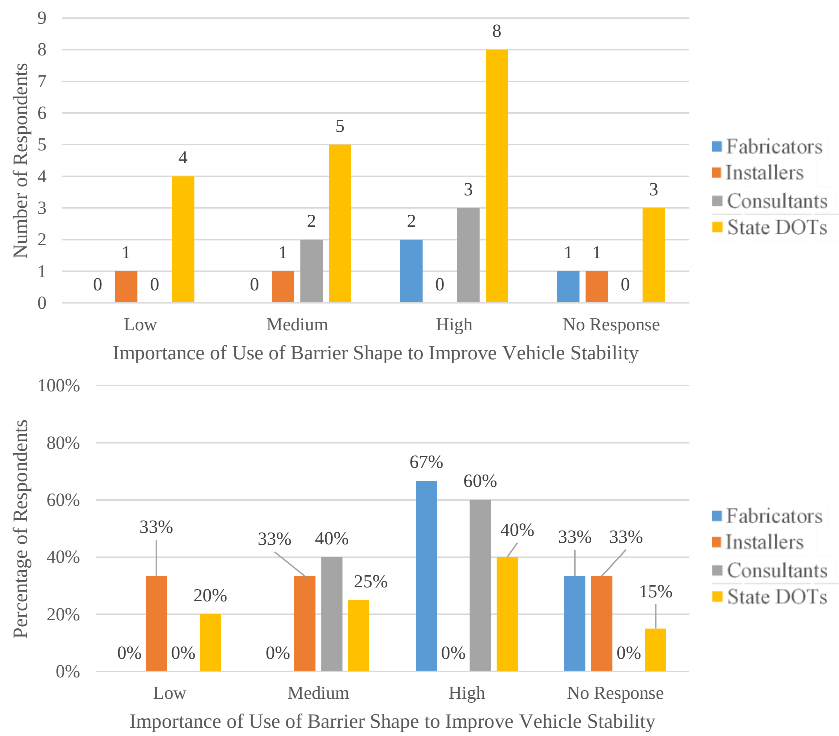


Figure 99. Importance of Improving Vehicle Stability – Responses by Organization

4.4.26 Question 26

Respondents were asked to choose a preferred barrier height, either 32 in. or less than 32 in., as shown in Figure 100. Barriers shorter than 32 in. may complicate future transitions to existing barrier systems. Majority of respondents, 18 (58 percent), responded with 32 in., nine (29 percent) responded with less than 32 in., and four (13 percent) did not respond.

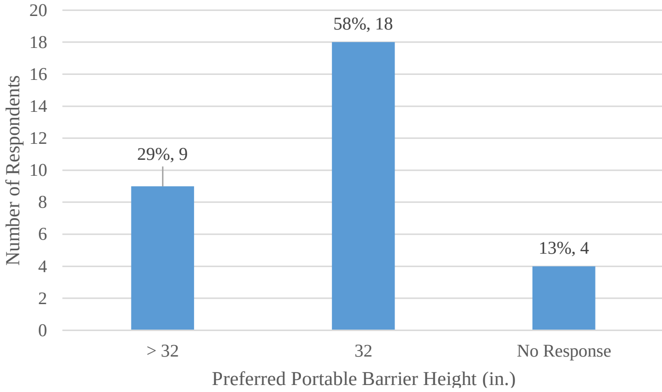


Figure 100. Preferred Portable Barrier Height – Total Responses

Responses by responding organization are shown in Figure 101. The three fabricators responded with less than 32 in. (one, 33 percent), 32 in. (one, 33 percent), and no response (one, 33 percent). All three installers (100 percent) responded with 32 in. Two of the consultant respondents (40 percent) responded with less than 32 in. and three (60 percent) responded with 32 in. Majority of state DOTs (11, 55 percent) responded with 32 in., six (30 percent) responded with less than 32 in., and three (15 percent) did not respond.

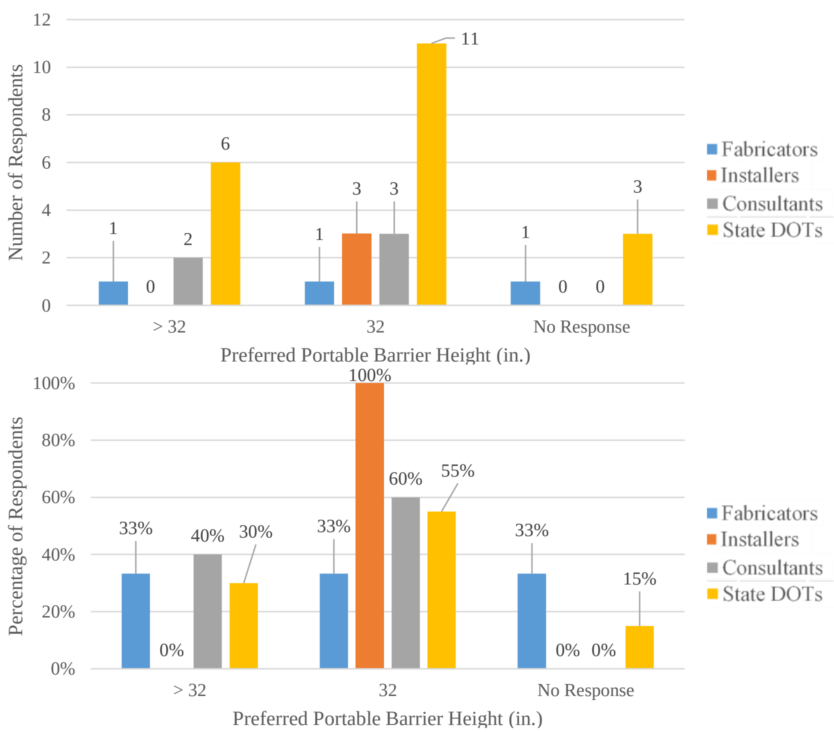


Figure 101. Preferred Portable Barrier Height – Responses by Organization

4.4.27 Question 27

All respondents were asked if there was a desire to develop a portable barrier system to meet MASH TL-4. Responses are shown in Figure 102. Twelve respondents (39 percent) responded yes, 14 (45 percent) responded no, and five (16 percent) did not respond.

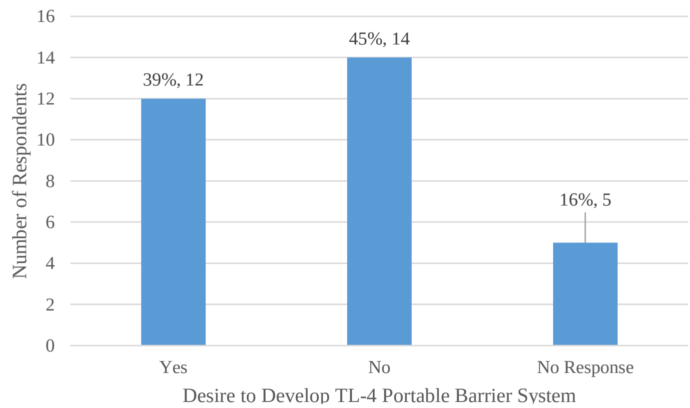


Figure 102. Desire to Develop TL-4 Portable Barrier System – Total Responses

Two fabricators (67 percent) responded with yes and one (33 percent) gave no response, as shown in Figure 103. Two installers (67 percent) responded no and one (33 percent) gave no response. Consultants responded with yes and no, with two (40 percent) saying yes and three (60 percent) saying no. State DOTs responded with yes, no, and no response, with eight (40 percent), nine (45 percent), and three (15 percent), respectively.

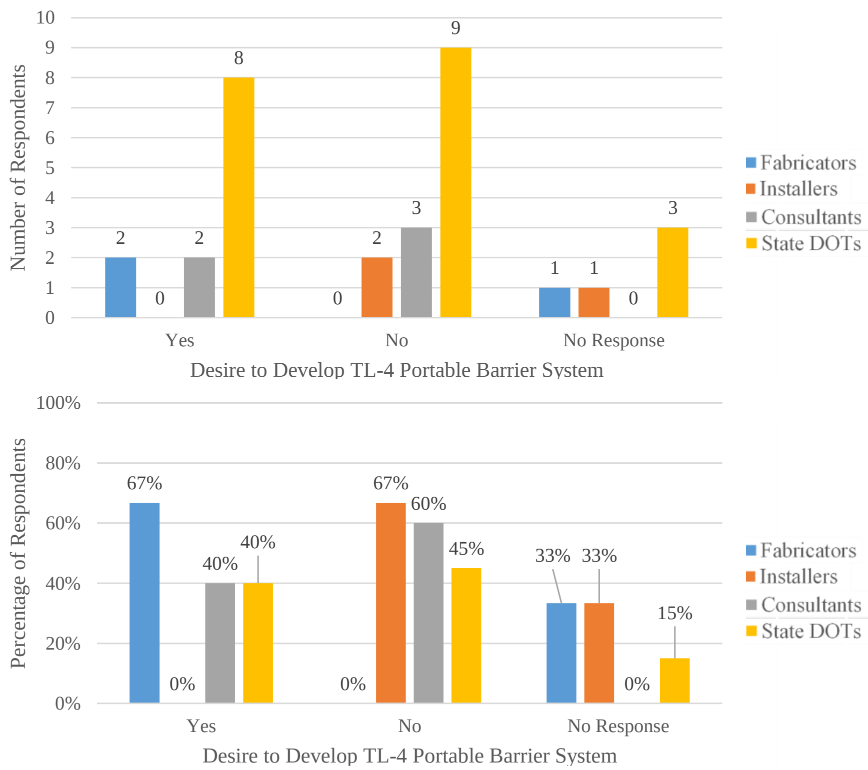


Figure 103. Desire to Develop TL-4 Portable Barrier System – Responses by Organization

4.4.28 Question 28

Question no. 28 asked respondents for their preferred free-standing dynamic deflection, between 2 and 7 ft, in 1-ft intervals, as shown in Figure 104. Five respondents (16 percent) did not respond. The remaining 26 responses (84 percent) ranged between less than 2 ft up to 5 ft.

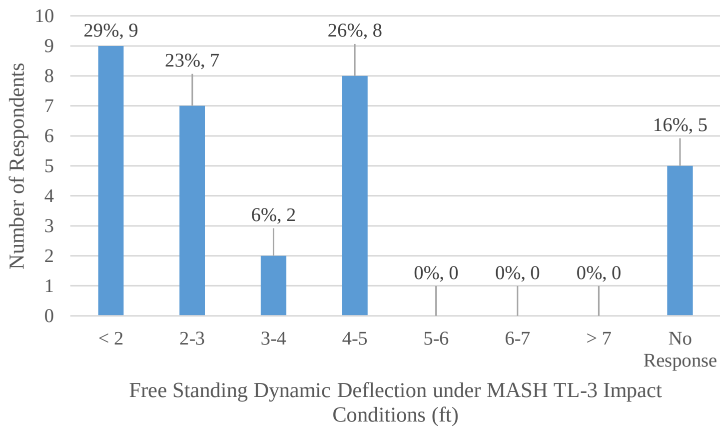


Figure 104. Free Standing TL-3 Dynamic Deflection – Total Responses

One fabricator (33 percent) noted a deflection of less than 2 ft and two (67 percent) did not respond, as shown in Figure 105. All installers (three, 100 percent) responded with 3 ft or less. All consultants (five, 100 percent) responded with 4 ft or less. Five state DOTs (25 percent) responded with less than 2 ft, four (20 percent) responded with 2 to 3 ft, eight (40 percent) responded with 4 to 5 ft, and three (15 percent) gave no response.

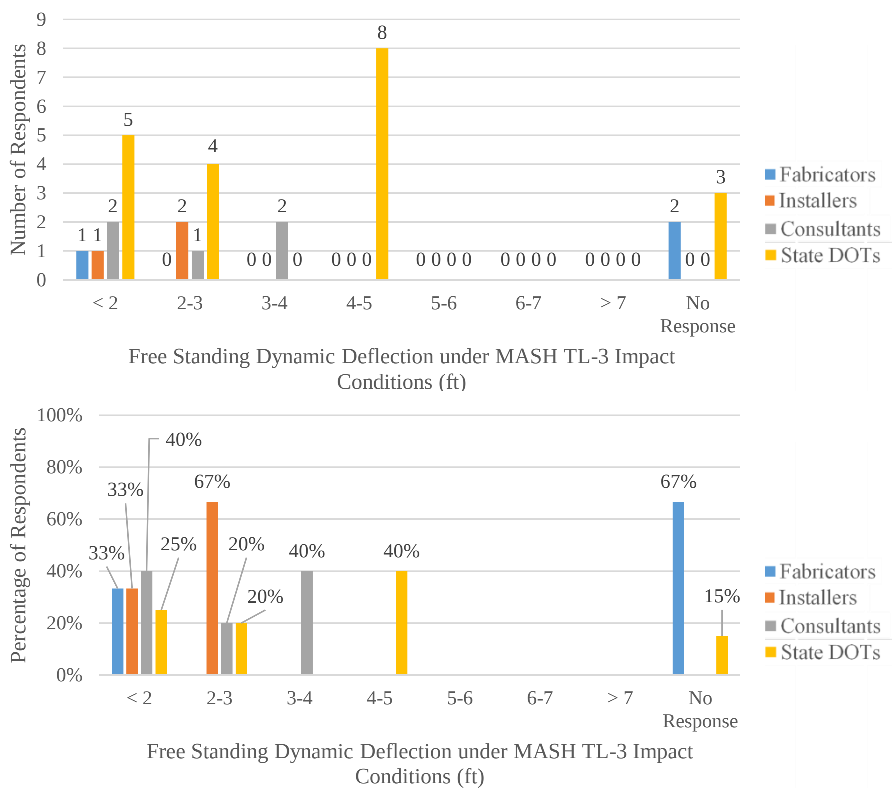


Figure 105. Free Standing TL-3 Dynamic Deflection – Responses by Organization

4.4.29 Question 29

Respondents were asked to note the type of road surface or surfaces through which they would anchor portable barriers, including asphalt, concrete, concrete with asphalt overlay, graded shoulder or gravel, bridge deck, or other (not specified), as shown in Figure 106. Note, respondents were allowed to respond with multiple surfaces, so the total number of responses is greater than 31, the number of respondents.

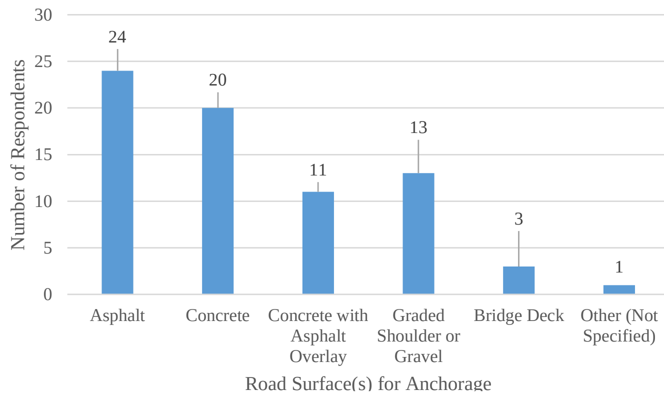


Figure 106. Road Surface for Anchorage – Total Responses

No fabricators responded to question no. 29, as shown in Figure 107. Installers responded with asphalt, concrete, concrete with asphalt overlay, graded shoulder or gravel, and bridge deck. Consultants responded with all surfaces except bridge decks. State DOTs noted all road surfaces are used and one state DOT selected other but did not specify a road surface.

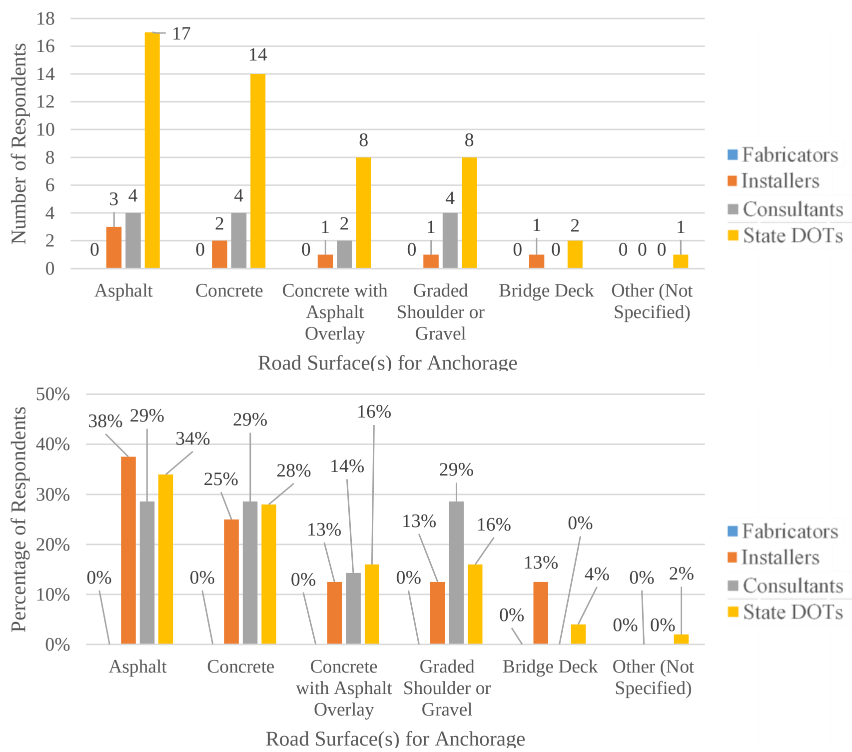


Figure 107. Road Surface for Anchorage – Responses by Organization

4.4.30 Question 30

Respondents were asked to specify which type of barriers to which the new portable barrier might be attached, including permanent F-shape, New Jersey, single slope, and vertical barriers, steel bridge rails, W-beam guardrail or Midwest Guardrail System (MGS), thrie beam guardrail, anchored portable barriers, crash cushions, or other (not specified). Responses are shown in Figure 108. Note, respondents were allowed to respond with multiple barrier systems, so the total number of responses is greater than the 31 respondents.

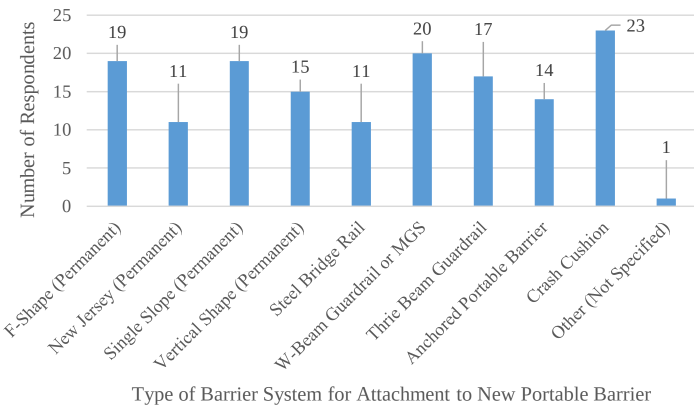


Figure 108. Type of Barrier System for Attachment – Total Responses

Responses by responding organization are shown in Figure 109. Fabricators responded with permanent F-shape barriers and crash cushions. Installers, consultants, and state DOTs noted all types of barrier systems would be used. One state DOT responded with other but did not specify which type.

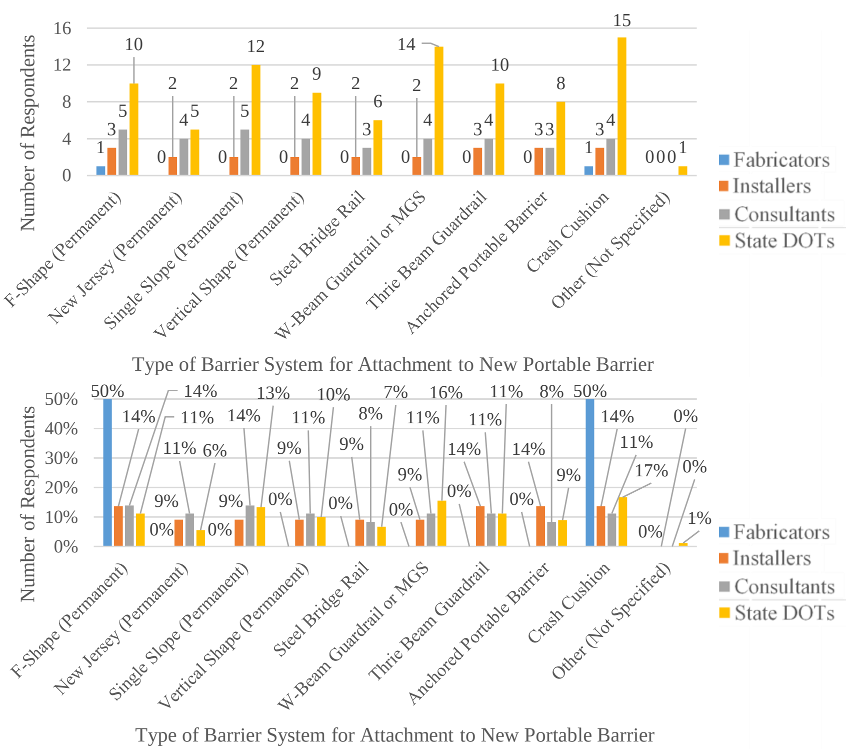


Figure 109. Type of Barrier System for Attachment – Responses by Organization

4.4.31 Question 31

The last question on the survey asked respondents to note any other important design considerations for the new portable barrier system or additional comments. These notes and comments are summarized below.

1. Switching to a new portable barrier system will be a large cost investment for contactors when they have thousands of feet of current barriers.

2. Design the new portable barrier to minimize vehicle damage for low-angle impacts.

3. Improve the joint connections and connections to the road surface.

4. It is desired to be able to replace damaged barrier segments without removing multiple sections of the barrier installation.

5. A simple, easy joint connection is preferred.

6. It is desired to be able to verify correct connection installation from the traffic side of the barrier.

7. Low dynamic deflections and ability to pin to road surface for no deflection are requested.

4.5 Discussion

Cost was one of the most important aspects of the new portable barrier system for all respondents. Majority of respondents were willing to accommodate higher costs if the barrier had a longer service life cycle than current barriers. Installers are typically the purchasers of portable barrier inventory, and they requested a portable barrier cost of less than $100 per ft. For a 12-ft barrier segment length, this equates to $1,200 per segment, which is slightly higher than the current cost for the F-shape PBCs with pin and loop connections.

For material, concrete was the most preferred, followed by steel and then plastic. Respondents were fine with ballasting steel or plastic designs if those are chosen. Furthermore, if concrete is chosen, respondents were willing to explore alternative concrete options.

Regarding operational preferences, respondents noted that easy transport and easy installation of the new barrier is of high importance. In addition, an easy connection which is easy to inspect for correct installation is critical.

Respondents were asked for their preferred barrier geometry. Majority of respondents requested a barrier weight up to 7,000 lb, and a barrier length between 10 and 14 ft was preferred. Many current barriers are 12.5 ft, which could be the length of the new barrier for consistency. To improve vehicle behavior, a vertical or near-vertical shape was preferred. Majority of respondents requested a 32-in. tall barrier for an easy transition to current barriers.

For drainage, a wide range of values were supplied by respondents. Consequently, current designs will be reviewed to determine the range for drainage needs. Ability to accommodate flare rate, or horizontal radius of curvature, was ranked as high importance and values between 100 and 770 ft were reported. Vertical curvature was also addressed and reported values ranged up to 6 percent. However, this value is higher than expected so further review may be necessary.

Respondents noted that this new portable barrier will be connected to numerous types of barriers, including concrete barriers, steel bridge rails, guardrail, and crash cushions, therefore transition segments may need to be designed.

Finally, desired dynamic barrier deflection was questioned, and majority of respondents requested a free-standing deflection less than 3 ft. Design considerations for anchorage to further limit deflections were also highly desired.

5 DESIGN CRITERIA

The objective of this research was to develop a high-performance portable barrier capable of meeting MASH TL-3 safety requirements with reduced free-standing barrier deflections and increased vehicle stability as compared to existing PCB systems. The researchers reviewed the literature search and end user survey results and developed basic design criteria for the new portable barrier system. These design criteria would be applied to the development and evaluation of potential design concepts. Note that any one design may not be able to meet all design criteria, but the design concepts developed in the project strive to capture as many of the criteria as possible.

5.1 Cost

The current 12.5-ft long F-shape PCB developed by the Midwest Pooled Fund Program can be purchased for approximately $600 to $1,000 per unit, including shipping costs ($48 to $80 per linear foot). To be a competitive and viable option, a new portable barrier would need to cost approximately the same or less than current designs. If the new barrier design was more expensive, it would need to have a longer service life than current PCBs, making it more cost effective.

According to majority of survey respondents, cost was ranked as medium importance. Furthermore, 84 percent of respondents were willing to accommodate higher costs for increased barrier durability and service life. When asked for the acceptable cost per foot of barrier for a barrier with a service life twice as long as current barriers or for a barrier to be reusable after a TL-3 impact, a majority of respondents (52 percent) responded with up to $100 per foot. Based on this information, the cost of the new portable barrier is targeted to be less than or equal to $100 per linear foot with a focus on increased durability.

5.2 Material

The new portable barrier design was not limited to a specific material. Therefore, steel, concrete, and plastic were considered. Weight reductions could be achieved by using a steel or plastic design. However, major weight reductions from current PCB designs may not be desired as this tends decrease barrier inertial resistance and friction and increase barrier deflection.

In the survey, respondents were asked to rank concrete, steel, and plastic in terms of preference. For each material, approximately three-fourths of respondents ranked concrete as most preferred, steel as middle preferred, and plastic as least preferred.

Concrete is the most widely used material for portable barriers and has an estimated cost of $125 per cubic yard or $0.03 per lb. Steel is more robust than other materials, but also more expensive at an estimated cost of $2.50 per lb. Plastic costs vary on based on the type of plastic material and the manufacturing method.

Plastic barriers were ruled out for the design of the new barrier due to their low ranking in the survey, concerns with their structural capacity, and low inertial resistance. These shortcomings have been observed in previous proprietary plastic portable barriers which displayed high dynamic deflections and often required steel reinforcement and water to satisfy TL-3 impact conditions.

To gain more insight into the use of steel barriers, the researchers compared the existing portable concrete and steel barriers. Several Midwest Pooled Fund states utilize a 12.5-ft long F-shape PCB [4]. One barrier section weighs approximately 5,000 lb and costs between $600 and $1,000 each. This equates to $48 to $80 per foot. The Iowa Department of Transportation has previously used a nonproprietary, steel, portable barrier named the H-barrier that was made up of stacked and welded H-sections [37]. The H-barrier is a 20-ft long steel barrier with a mass of 6,200 lb; 3,000 lb of steel and 3,200 lb of concrete. The use of concrete ballast in the barrier helped maintain reasonable dynamic barrier deflections. When only the steel is considered, this equates to $325 per foot. This is significantly more expensive, but the H-barrier has been observed to be more durable than the concrete F-shape barriers and resists damage when impacted sufficiently to be reusable. Therefore, the life span of the H-barrier would be significantly greater than that of concrete barriers. However, the cost is 5.8 times that of concrete portable barriers at a minimum. Thus, steel was still considered a viable barrier design material. However, durability and dynamic deflection of any potential steel portable barrier design would need to be sufficient to offset the associated cost.

Alternative concrete materials were observed to provide several potential benefits in terms of reduced cracking and damage. However, there were concerns with the costs associated with the alternative concretes. Additionally, local precast manufacturers may not currently have a high degree of experience with alternative concretes or appropriate equipment for fabrication of these materials, thus their availability may be limited. Thus, it was recommended to focus on standard concrete mixes for the new barrier design with the caveat that alternative concretes should be considered in future research to improve a potential portable concrete barrier developed in this project.

5.3 Durability

According to survey results, 90 percent of respondents ranked durability as medium or high importance. No research exists detailing the service life of portable barriers. There are limited life expectancy guidelines for PCBs that define damage which would require barrier segment repair or replacement. Because of this, contractors and DOTs are forced to make judgement calls, which can result in unacceptable barriers being used in work zones.

In state DOT responses to the survey in NCHRP 22-36 regarding portable barrier inspection, multiple states noted there are no inspection guidelines or criteria for determining when a portable barrier should be retired. Several state DOTs have developed their own inspection and replacement guidelines over time, but this guidance is not widely distributed or researched. Damaged portable barriers will not perform to standards and may result in higher than anticipated deflections or vehicle penetration through the system.

Many PCBs have service lives of approximately five to ten years according to an informal survey of contractors and end users. For the new portable barrier design, it is desired to maintain or increase the service life of the new barrier through improved barrier geometry and structural design to limit damage during impact, installation, and transportation. Based on this, the researchers decided to focus on increasing durability of the portable barrier concepts while attempting to meet the cost targets noted previously.

5.4 Installation

5.4.1 Transportability

Transporting portable barriers from inventory to the work site is a time consuming and costly aspect of a construction job. Barriers must be placed on trucks, transported to the site, lifted down, and placed. To minimize cost of transport, barrier packing on trucks should be optimized, with a practical length and width for placement on transport trucks. Many barriers, especially safety shape barriers, are damaged at the toe during transport or placement due to lack of reinforcement. Furthermore, lifting slots or attachments may need to be incorporated into the barrier.

5.4.2 Weight

Portable barriers range in weight between 1,500 lb to 14,000 lb. The weight of portable barrier segments heavily depends on material, cross-sectional geometry, and section length. NCHRP 22-36 reported a typical forklift lifting capacity between 2,500 and 5,000 lb [9]. Heavier barriers would require stronger lifting equipment, which may need to be specially purchased by contractors. Furthermore, tractor-trailers have to abide by weight limits during transport. If barriers segments were lighter then fewer trips would be required, reducing transport costs.

While reducing portable barrier weight would reduce costs for transport, the barriers need to provide inertial resistance when impacted. A barrier with the same or similar mass compared to current PCBs, approximately 5,000 lb, would provide the correct balance between reducing transportation cost and maintaining impact resistance. According to survey results, only 35 percent of respondents reported being unable to accommodate barrier weights of up to 7,000 lb. Thus, weight criteria for the design were established to limit the lifting weight of the barrier segments to less than 7,000 lb.

5.4.3 Geometry

The new portable barrier was not limited to a certain barrier shape. Full-scale crash tests, in-service performance evaluations, and state DOT surveys were utilized to determine barrier geometry design criteria.

5.4.3.1 Shape

Based on an in-service performance evaluation of safety shape and vertical shape barriers [27] and full-scale crash testing of safety shape barriers, a vertical or nearly vertical barrier shape was desired. This would minimize or eliminate vehicle climb and roll during impact, which would reduce the chance of vehicle rollover. Impact forces and occupant accelerations would be higher for vertical barriers, but portable barriers allow for barrier deflection, which would reduce accelerations.

Respondents to the survey for this research study were asked to rank the importance of using a vertical or near-vertical barrier shape to reduce vehicle climb and roll to improve vehicle stability. A total of 68 percent of the respondents ranked this as medium or high importance.

According to a representative from Concrete Industries, for manufacturing purposes, a draft of 0.5 in. per foot would need to be incorporated into the barrier sides, resulting in a near-vertical shaped barrier with a draft of 2.4 degrees. This draft would allow the cured concrete barrier to strip out of the form without moving the sides.

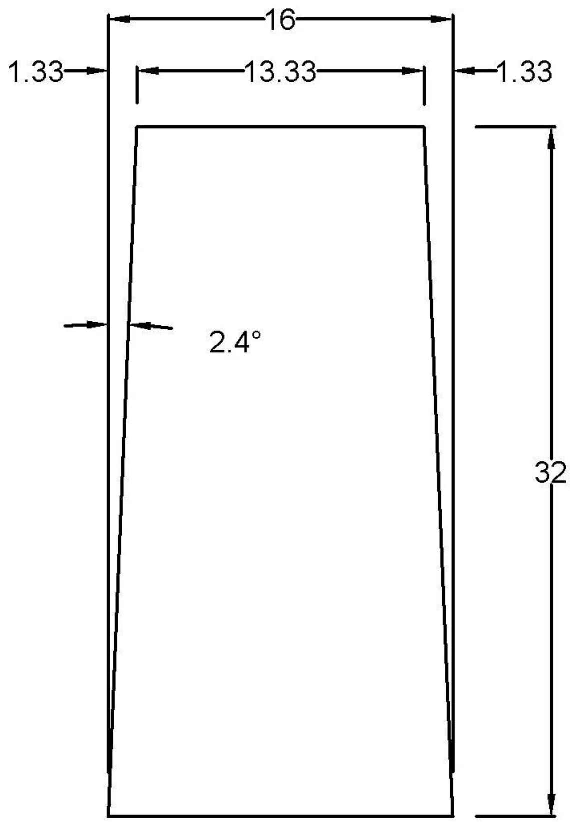


Figure 110. Proposed Barrier Shape – Near Vertical with a 2.4-Degree Draft

5.4.3.2 Length

Portable barrier sections range in length from 3.25 ft to 30 ft long. Larger section lengths result in fewer connection joints between barrier sections. When impacted, rotation occurs around the joint connections. Therefore, larger section lengths, which have fewer connections, result in lower deflections. However, barriers sections must be transported and positioned by equipment which has size and weight limits.

Typical barrier section lengths are 10, 12.5, 20, and 30 ft [9]. Texas is the only state which utilizes 30-ft section lengths, and contractors within the state had to adjust to accommodate them [9]. Within the DOT survey responses in NCHRP 22-36 [9], multiple states requested 12- or 12.5-ft long sections, and 62 percent of respondents requested a barrier segment length of less than 14 ft. A barrier segment length of 12.5 ft was targeted for the new portable barrier design based on these responses and consistency with current PCB designs.

5.4.3.3 Height

Previous NCHRP Report 350 and MASH TL-3 barriers have employed heights ranged between 26 in. and 46 in. Majority of portable concrete barriers and permanent concrete parapets meeting MASH TL-3 use a 32-in. height. Taller barrier designs are often employed for TL-4. Within the survey for this research study, respondents were asked which barrier height they preferred: less than 32 in. or 32 in. tall. A majority requested a 32-in. tall barrier. A 32-in. tall barrier also can also be more easily transitioned to current permanent and temporary barriers and guardrail already in use on the roadway. Thus, a 32-in. height was targeted for the new portable barrier concepts.

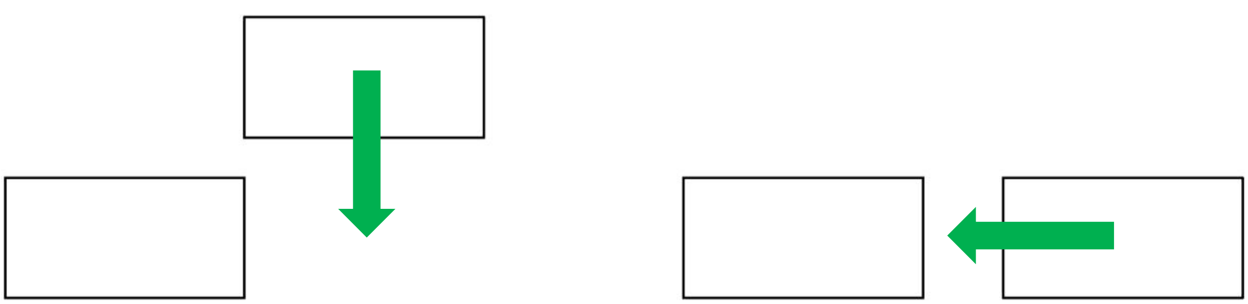
5.4.3.4 HW Ratio

The researchers reviewed the height-to-weight (HW) ration for previously crashed tested barrier systems. For NCHRP Report 350 and MASH TL-3 barriers, the HW ratio for a TL-3 barrier was between 1.12 and 2.0. State DOTs responded that they desired barrier base widths to be within the footprint of current safety shape PCBs which were typically 24 in. wide or less. This corresponded to a 1.33 HW ratio for a 32-in. tall barrier. Thus, the design of the new portable barrier would focus on meeting the maximum base width criteria while keeping the HW ration within the range of previously tested barriers. Smaller HW ratios may be achievable dependent on the torsional characteristics of the barrier connection.

5.4.4 Installation Ease

5.4.4.1 Barrier Placement

State DOTs requested symmetric connection designs to ease installation in the NCHRP 22-36 survey [9]. This would allow barriers to be oriented in either direction, which would reduce loading and placement time. Furthermore, barriers can be placed either vertically or horizontally, as shown in Figure 111, and certain connections only allow for one or the other. Ideally, the new portable barrier design would allow for both. According to survey results, 90 percent of respondents ranked ease of barrier placement as medium or high importance.



(a) (b)

Figure 111. Barrier Placement, (a) Vertical and (b) Horizontal

Within the survey for this research study, one respondent noted an additional installation request. The respondent wanted to be able to replace a damaged barrier segment without removing multiple sections of the barrier installation. A barrier which could be placed vertically would fit this request.

5.4.4.2 Connection

Barriers which require no hardware or tools would have the shortest installation time compared to barriers which require either or both. Hardware can be lost during transport to the work zone and some contractors may not have the appropriate tools for installation.

The connection for portable barriers must provide a combination of tensile, shear, and moment capacity to effectively connect and transfer load between barrier segments. The efficiency of the design (shear transfer and moment continuity) significantly affects the barrier performance in terms of dynamic barrier deflections and vehicle snag. The importance of connection installation ease was ranked as high importance by 84 percent of respondents. Multiple respondents requested simple joint connections. Based on these factors, the connection design for the new portable barrier was targeted to be simple to install without tools while providing improved the shear transfer and moment continuity across the joint.

5.4.4.3 Curvature Requirements

Portable barriers must also be able to accommodate horizontal and vertical curves. This concern was mentioned by multiple states in the survey response in NCHRP 22-36 [9] and by WisDOT. Furthermore, in the survey created for this research study, 90 percent of respondents ranked barrier ability to accommodate curves as medium or high importance.

Sixty-five percent of respondents to the survey did not give a value for the minimum radius of horizontal curvature. The remaining 11 respondents gave values between 0 and 770 ft. Next, respondents were asked to give a maximum flare rate, which ranged between 4:1 and 18:1. Finally, respondents were asked to give the maximum vertical curvature or maximum percent grade. For maximum vertical curvature, only two values were given: 1,000 and 1,200 ft. For maximum percent grade, values between 4 and 20 percent were given. Further review of current PCB designs will be required to determine curvature requirements.

5.4.4.4 Transition to Other Barrier Systems

In the survey for this research study, respondents were asked to which types of barrier systems the new portable barrier would be attached. These barrier systems include permanent F-shape barriers, permanent New Jersey barriers, permanent single slope barriers, permanent vertical barriers, steel bridge rails, W-beam guardrail or MGS, thrie beam guardrail, anchored portable barriers, and crash cushions. While these transitions would not be specifically addressed in this research, their accommodation would need to be considered in the design. It is noted that specific transition sections may need to be developed dependent on the new portable barrier configuration and the type of barrier to which it is desired to connect.

5.4.5 Drainage

Drainage slots, while not vital to the barrier impact performance, are necessary in portable barriers to prevent water flow issues in areas where barriers are installed. Multiple states noted the need for drainage in the survey responses in NCHRP 22-36 [9] and WisDOT specifically requested drainage. Responses from the survey for this study showed 87 percent of respondents ranking drainage as medium or high importance.

Respondents were asked for drainage slot dimensions in terms of drainage slot length per barrier length. Applicable responses ranged between 0 and 0.5, corresponding to no drainage slots to half of the barrier base removed as drainage slots. Further review of existing portable barrier drainage was recommended to better define drainage needs. While drainage would not be directly incorporated into the design concepts developed in this study, it was understood that it would need to be incorporated into the future development of preferred concepts identified in this research.

5.5 Safety Performance

5.5.1 MASH TL-3 Impact Conditions

The new portable barrier must perform under MASH evaluation criteria for roadside hardware. Because portable barriers are used in work zones with a range of speed limits, it must meet TL-3 test conditions.

5.5.2 Improved Stability

The new barrier must show improved vehicle stability during and after impact. Safety shape barriers result in high vehicle climb and roll when impacted, while vertical shaped barriers result in no vehicle climb. Consequently, safety shape barriers result in lower impact forces and occupant accelerations and vertical shaped barriers result in higher accelerations. The new portable barrier design will focus on a near-vertical shape to improve vehicle stability.

5.5.3 Deflection

A primary goal of this project was to design a portable barrier with the smallest deflection possible while meeting all other design criteria. Survey respondents were asked to give an acceptable dynamic deflection for free-standing MASH TL-3 impacts. Majority of respondents desired barrier deflections below 3 ft. As such, the design of the new portable barrier system will focus on limiting deflections below 3 ft and would attempt to reduce deflections further if possible.

5.6 Other Considerations

5.6.1 Anchorage

The new portable barrier was to achieve reduced deflections without anchorage. However, some situations may exist where anchorage to the pavement is required. Survey respondents noted multiple road surfaces on which these barriers may be anchored, including asphalt, concrete, concrete with asphalt overlay, graded shoulder or gravel, and bridge decks. While the current research effort will not develop and evaluate anchorage for the new portable barrier, design concepts will consider anchorage compatibility in the design.

5.6.2 WisDOT Requests

The Wisconsin Department of Transportation (WisDOT) also provided suggestions for design criteria and considerations as sponsors of this research effort for a new portable barrier system. These are listed in the subsequent sections.

5.6.2.1 Connection Inspection

When placed, portable barriers must be inspected to ensure the connection was installed correctly. Ideally, a "drive-by" inspection on one side of the barrier could be performed to ensure correct installation.

5.6.2.2 Crash Cushion Connection

WisDOT expressed interest in connection crash cushions to the ends of a portable barrier installation. Furthermore, they desired a non-unique end section to accomplish this if possible.

5.6.2.3 Transition to Permanent Barrier

WisDOT also expressed interest in a portable barrier-to-permanent barrier installation transition. This may require a unique transition section, specific to the type of permanent installation. However, because most permanent installations are 32 in. tall it was requested that the new portable barrier be of a similar height.

6 PORTABLE BARRIER DESIGN CONCEPTS

Design concepts for a new portable barrier were created following the literature review and development of the portable barrier design criteria. Drainage, lifting, and anchorage features are not included in the concept designs, but will be incorporated into the design concepts when preferred designs are selected for further development. Full structural details were also not designed for the concepts at this time. However, the basic structural capacity of the barrier segment and the connection had to be considered reasonable to be considered a potential concept. Note that concept numbers were based on the order in which the concepts were developed by the researchers and some concepts that were deemed infeasible are not shown. As such, some concept numbers are omitted.

6.1 Concrete Designs

Potential new portable barrier designs made primarily from concrete are discussed in the following sections. For these designs, an alternate concrete could be utilized in place of regular Portland cement concrete. For manufacturing purposes, the barriers will feature a 2.4-degree taper on the sidewalls so the barrier segments can easily be removed from the mold. This taper is not shown in the concept drawings.

6.1.1 Concept No. 1

Concept no. 1 featured two plates and four pins per joint connection, as shown in Figures 112 through 114. The plates slide horizontally into slots in the face of the barrier and four pins (two in each barrier end) are dropped through the barriers and plates. The use of dual pins and plates in this concept would provide increased moment continuity and reduced rotation at the barrier joint. The design also allowed for a minimal gap between barrier segments, which should further aid in reducing barrier deflections. This PCB design required pin and plate hardware but required no tools and can be placed vertically or horizontally. Note that the pins in this concept could be placed side by side laterally, as shown, or longitudinally.

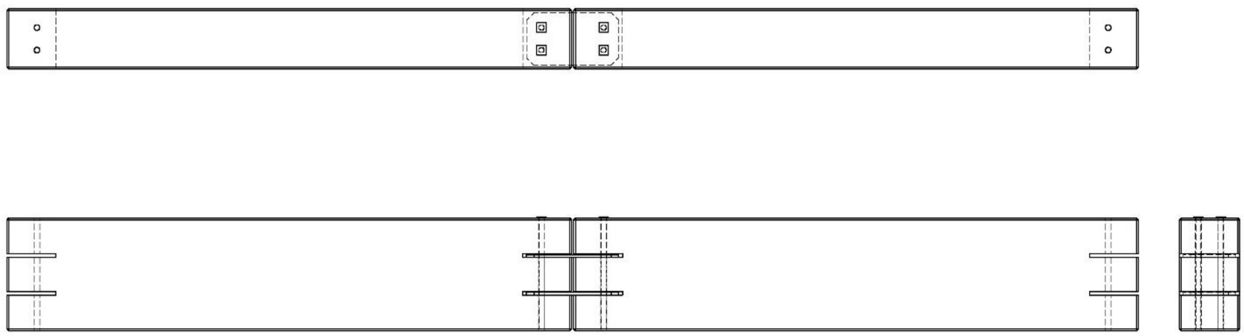


Figure 112. Concept No. 1

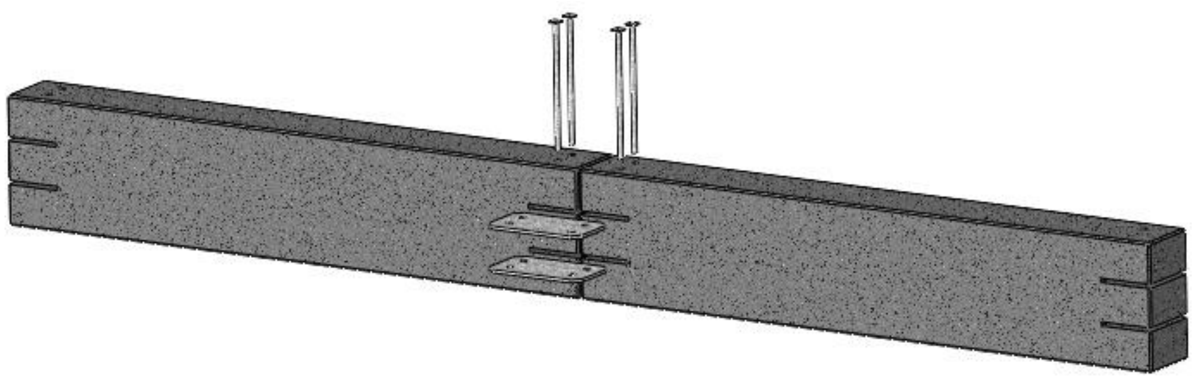


Figure 113. Concept No. 1 Parts

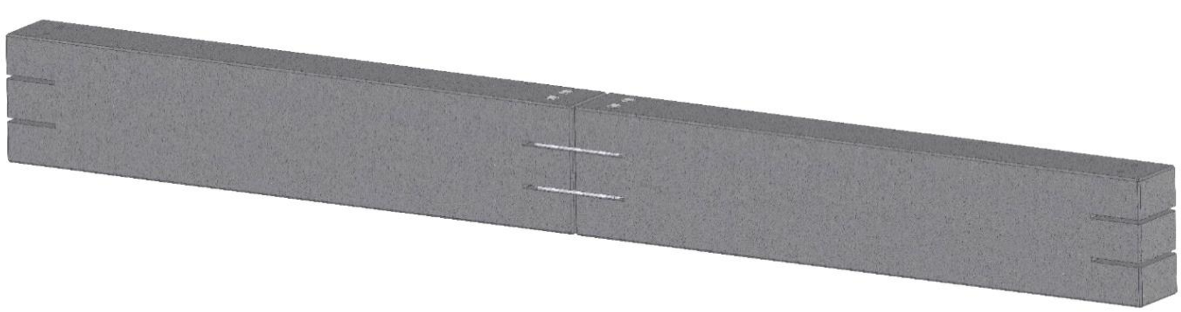


Figure 114. Concept No. 1 Assembled

6.1.2 Concept No. 2

The second concept is similar to concept no. 1 except that the barrier segment was made narrower and steel angles were added to the base of the barrier to improve stability and accommodate future anchorage, as shown in Figures 115 through 117. Six feet are bolted to each barrier section, three on each side, and anchors can be placed through the feet into the ground. This concept is shown in a narrower width in the figures for potentially reducing the mass and width of the concrete section, but this same steel angles could be added to concept no. 1 as well. Note that the pins in this concept could be placed side by side laterally, as shown, or longitudinally.

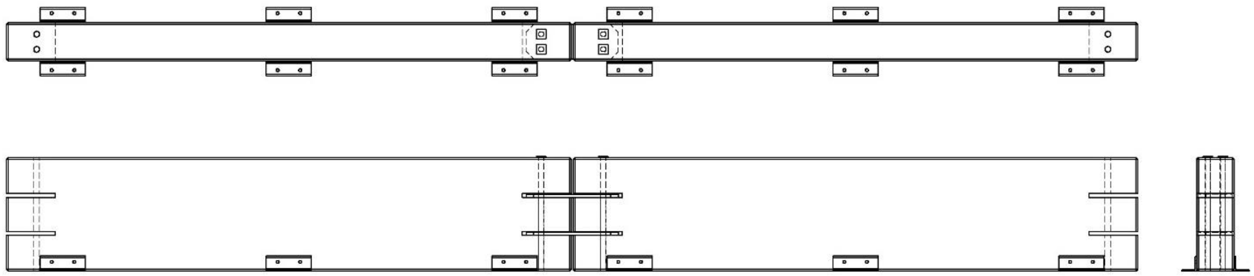


Figure 115. Concept No. 2

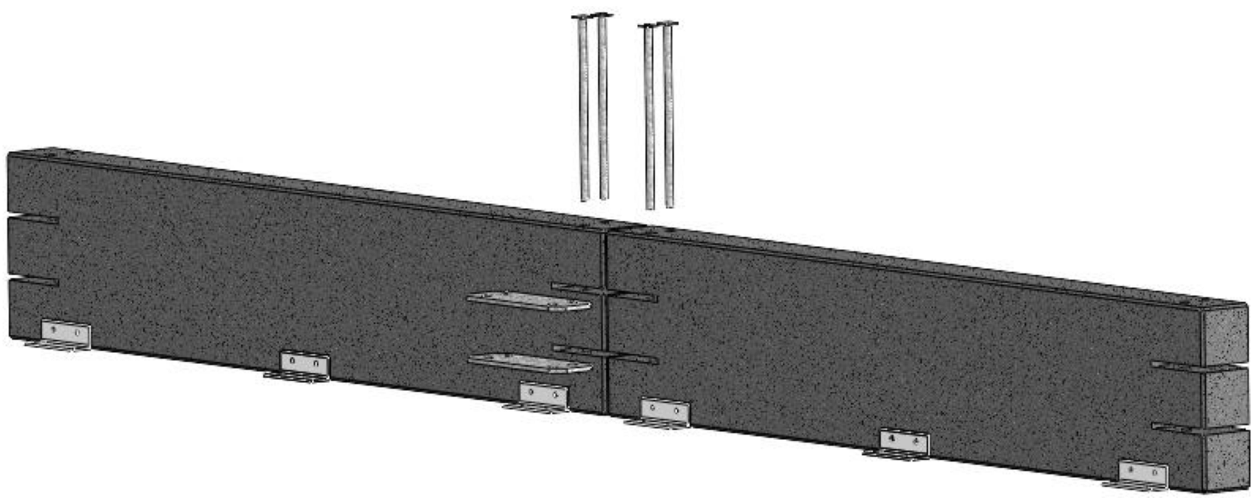


Figure 116. Concept No. 2 Parts

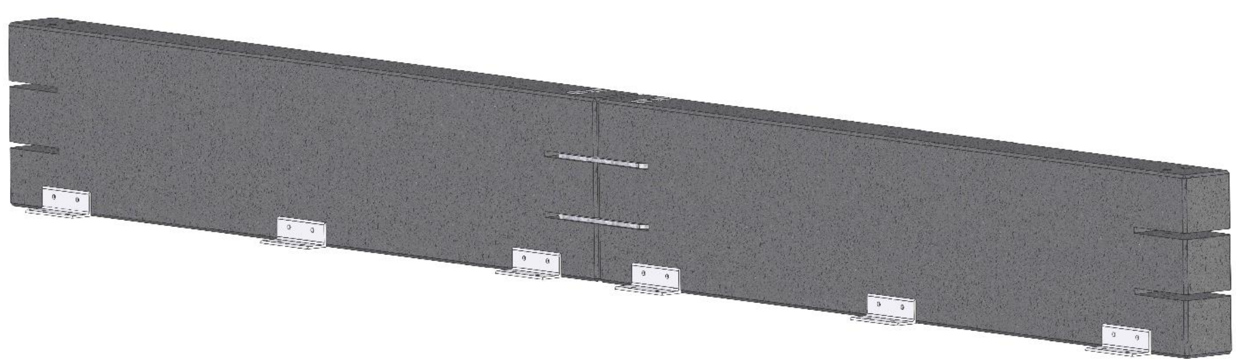


Figure 117. Concept No. 2 Assembly

6.1.3 Concept No. 3

Concept no. 3 is a third variation of concept no. 1. This concept features two plates per connection, one of which is placed on top of the barrier while the other slides into a slot approximately three quarters of the way down the face of the barrier segment. Four pins are dropped through the plates and barrier to complete the connection, as shown in Figures 118 through 120. Note that the pins in this concept could be placed side by side laterally, as shown, or longitudinally.

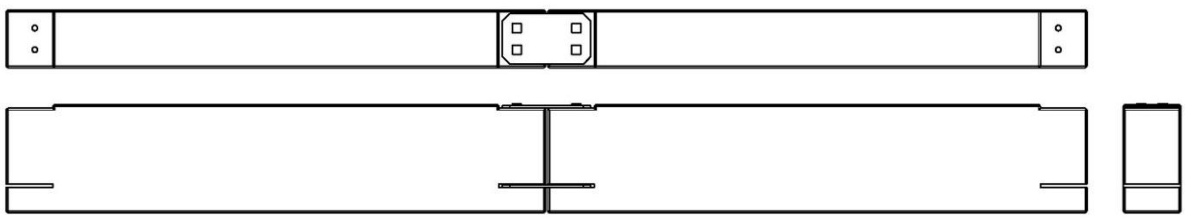


Figure 118. Concept No. 3

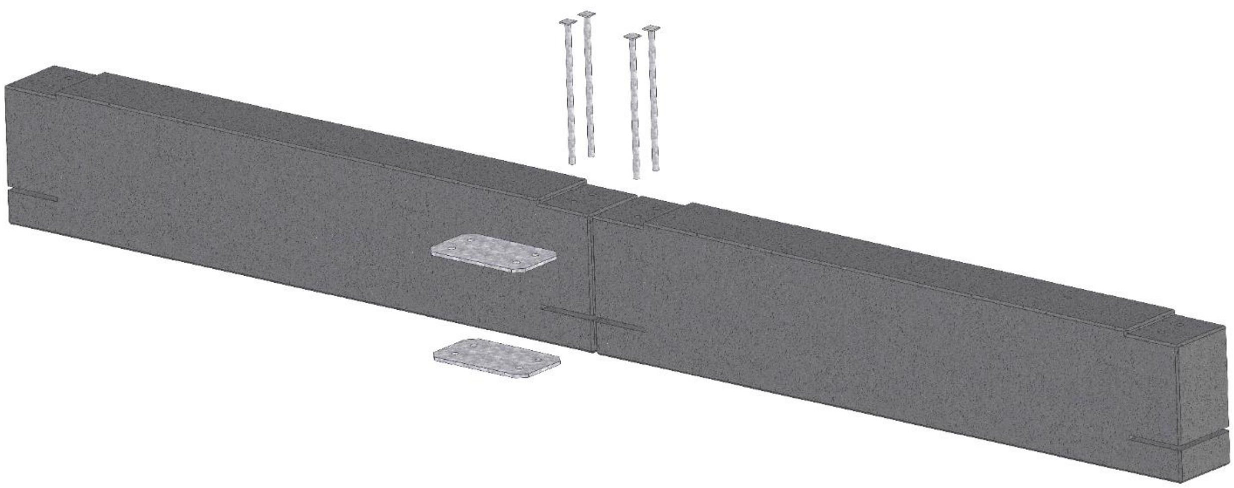


Figure 119. Concept No. 3 Parts

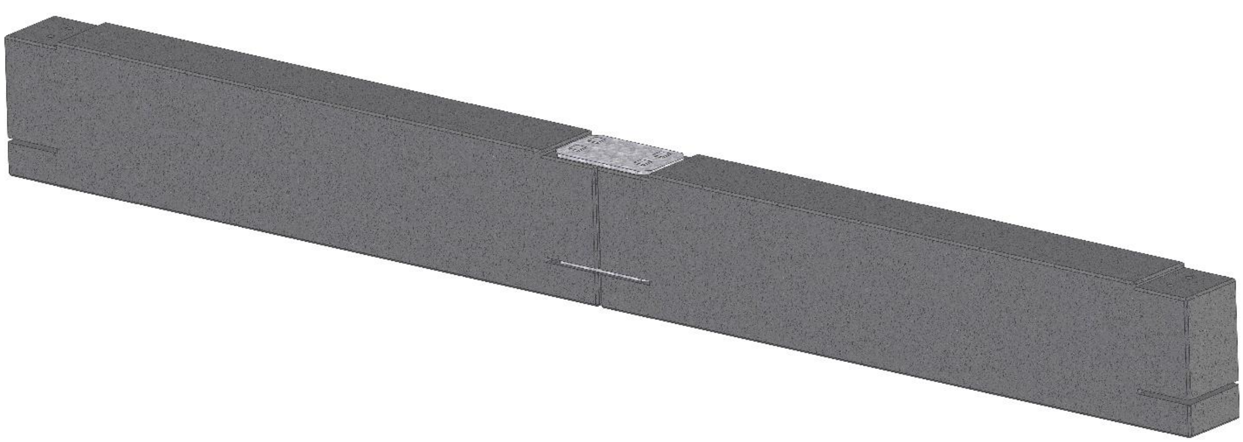


Figure 120. Concept No. 3 Assembly

6.1.4 Concept No. 4

The fourth concept features a key and keyway connection with an I-section shaped key, as shown in Figures 121 through 123. This connection allows for barriers to be placed either vertically or horizontally and requires one piece of hardware per joint. Note that this connection design does not provide for the degree of moment continuity in concept nos. 1 through 4, and it may not reduce barrier deflection as effectively.

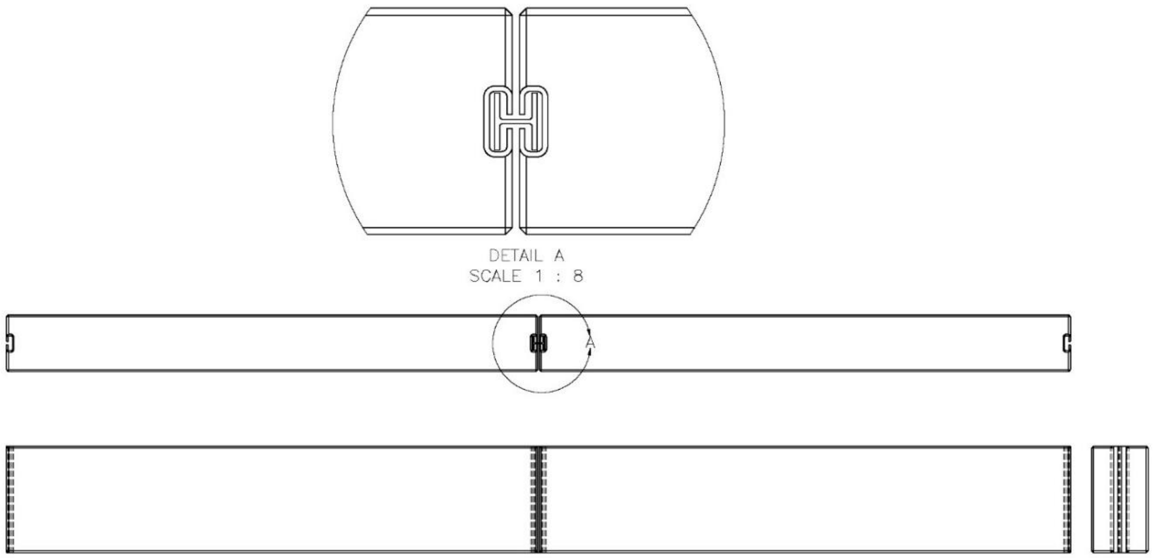


Figure 121. Concept No. 4

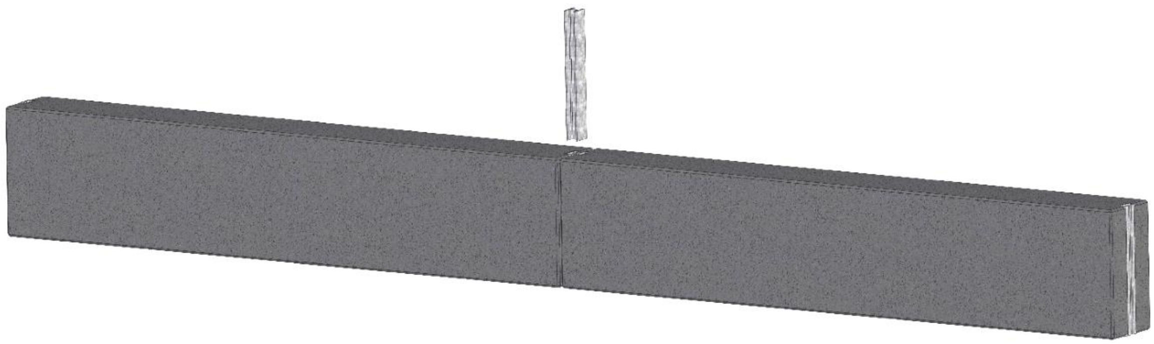


Figure 122. Concept No. 4 Parts

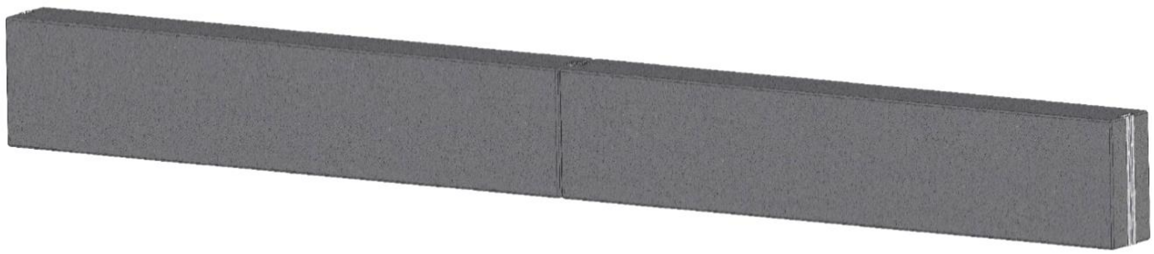


Figure 123. Concept No. 4 Assembly

6.1.5 Concept No. 5

The connection featured in concept no. 5 features two recesses in each barrier end where a rectangular tube will be inserted to span the two barriers, as shown in Figures 124 through 126. At each joint, two pins are dropped through the barriers and tube inserts. Because the tube must extend into the adjacent barrier segment in this connection, barriers can only be placed horizontally during installation.

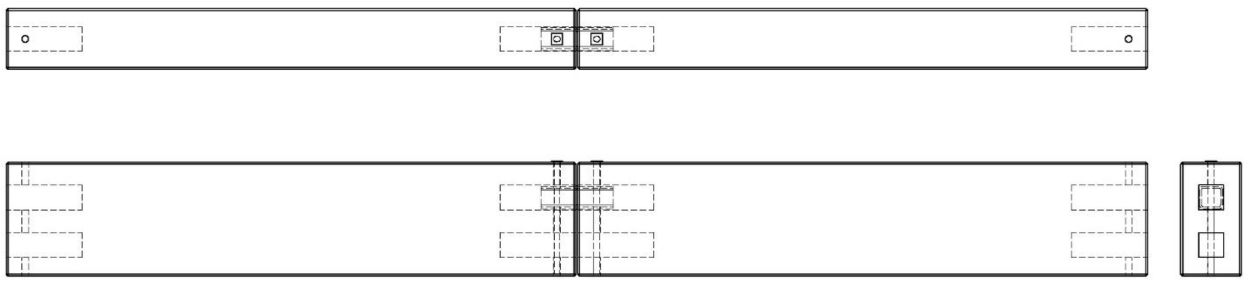


Figure 124. Concept No. 5

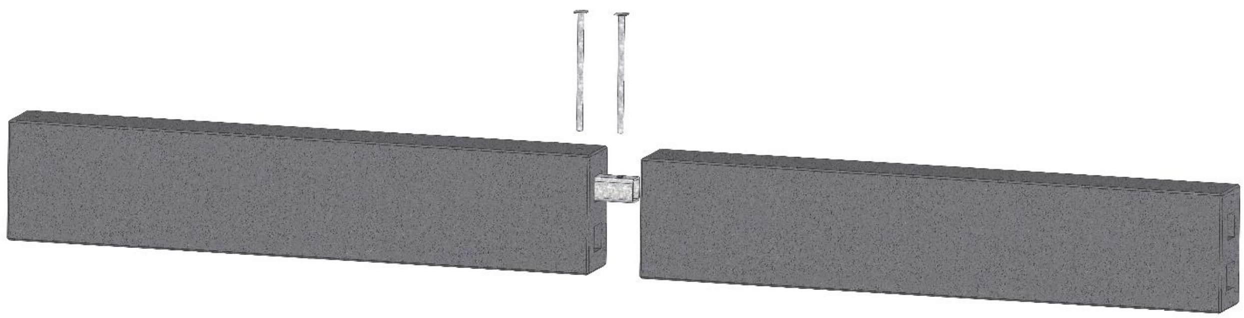


Figure 125. Concept No. 5 Parts

Figure 126. Concept No. 5 Assembly

6.1.6 Concept No. 6

Concept no. 6 is shown in Figures 127 through 129. This design features an irregularly shaped barrier with ends that fit together. Two pins are dropped into holes cut into the barrier to connect adjacent sections. The connection design eliminated the use of additional plates or tube hardware, but limited the installation flexibility to some degree as the barrier segments are non-symmetric and must installed horizontally. There were also concerns about concentrating the connection loading through a narrow section of the concrete barrier. Special end sections may also be required for this barrier concept due to its irregular barrier end geometry.

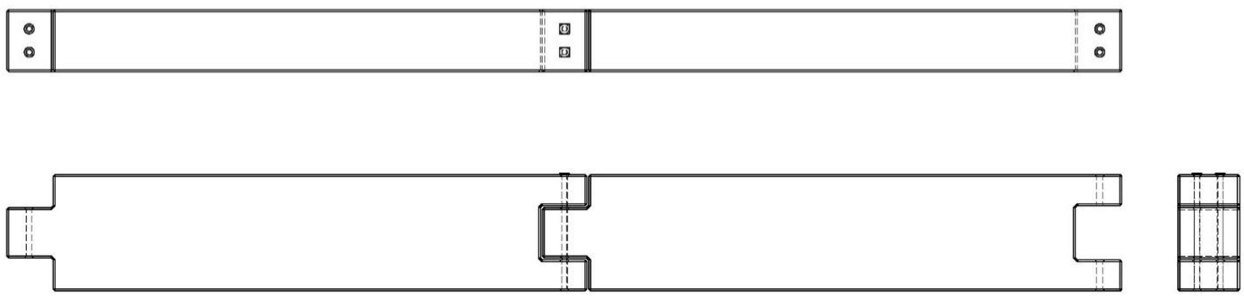


Figure 127. Concept No. 6

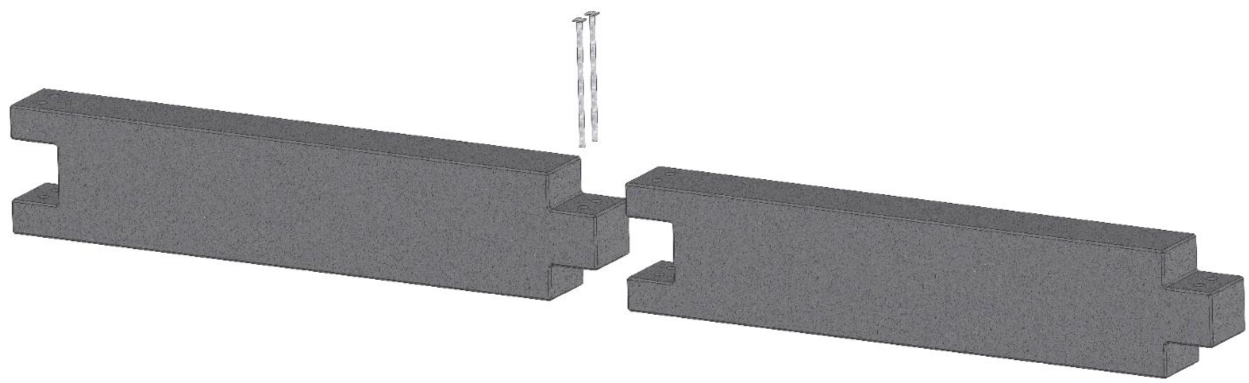


Figure 128. Concept No. 6 Parts

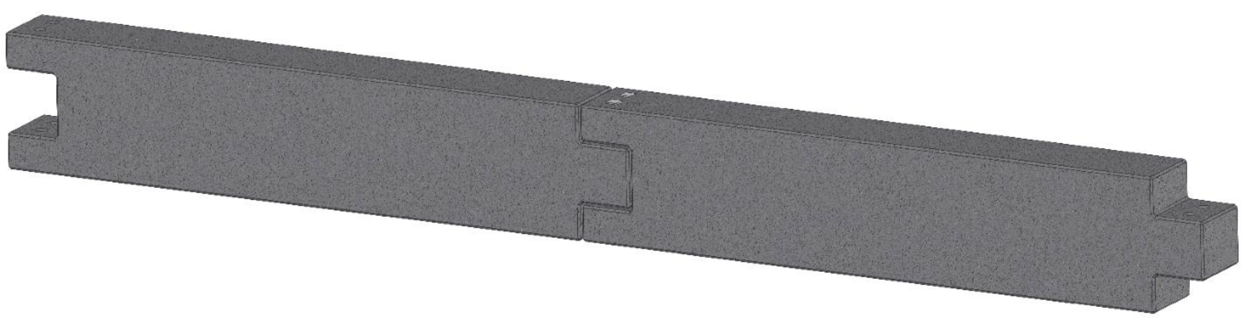


Figure 129. Concept No. 6 Assembly

6.1.7 Concept No. 7

The connection design in concept no. 7 features two plates cast into each end of the barrier segment, as shown in Figures 130 through 132. The corners of the concrete barrier are chamfered, exposing the corners of the plates. The extruded corners of the plate feature holes for a pair of vertical pins connected by a welded top plate to drop through. A second plate would hold the lower portion of the pair of vertical pins together. This connection design allows barriers to be placed vertically or horizontally. However, there were concerns with the number of connection pieces required for this connection and the load transfer of the plates and pins.

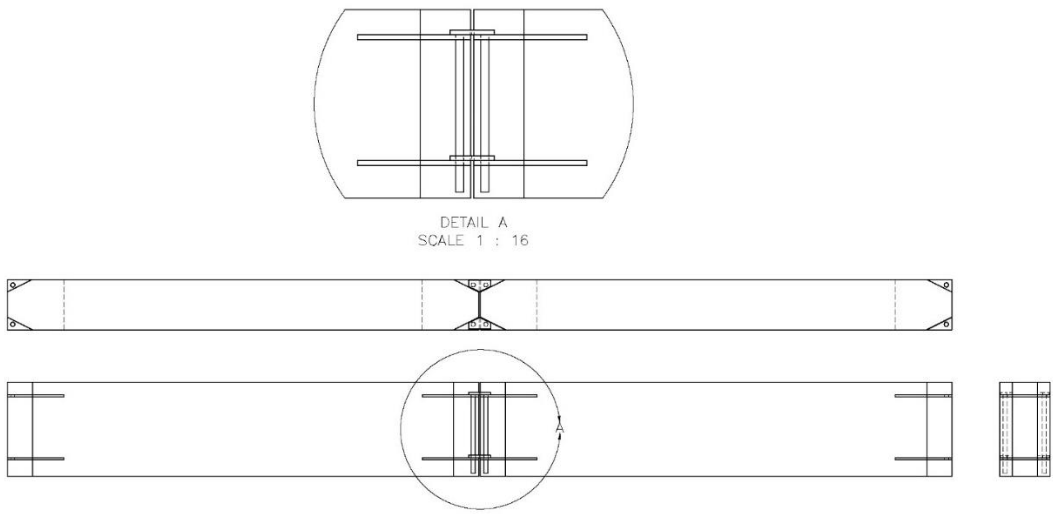


Figure 130. Concept No. 7

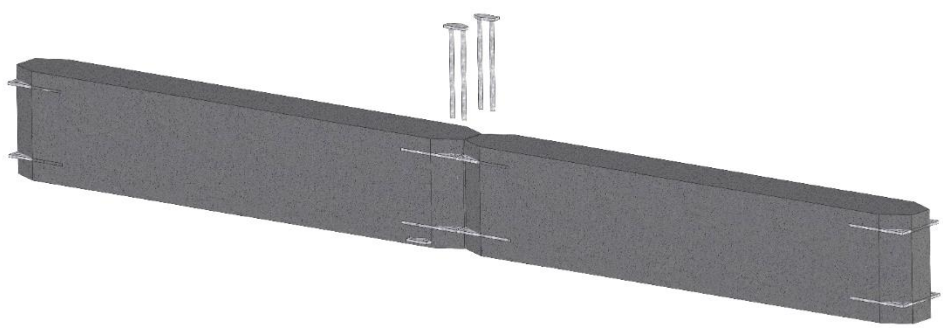


Figure 131. Concept No. 7 Parts

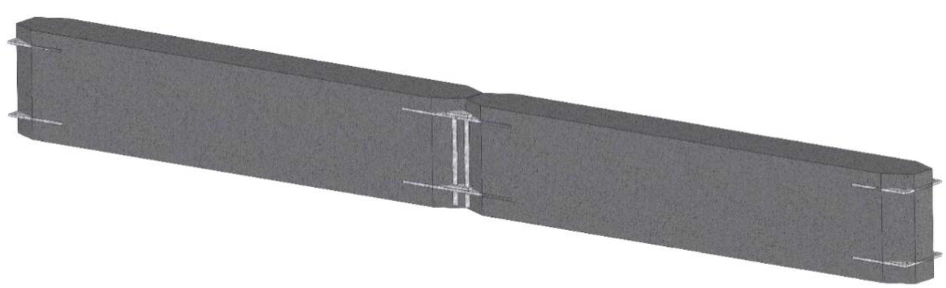


Figure 132. Concept No. 7 Assembly

6.1.8 Concept No. 8

Concept no. 8, as shown in Figure 133, features a T-shaped barrier with two plates and four pins per connection joint. The plates are mounted on the upper T section and span the connection. The pins drop through the plates and barrier section. This barrier design may be placed horizontally or vertically. This connection design required multiple hardware pieces to connect the segments, and there were concerns about focusing the load transfer at the connection through only the upper T-section of the barrier segment.

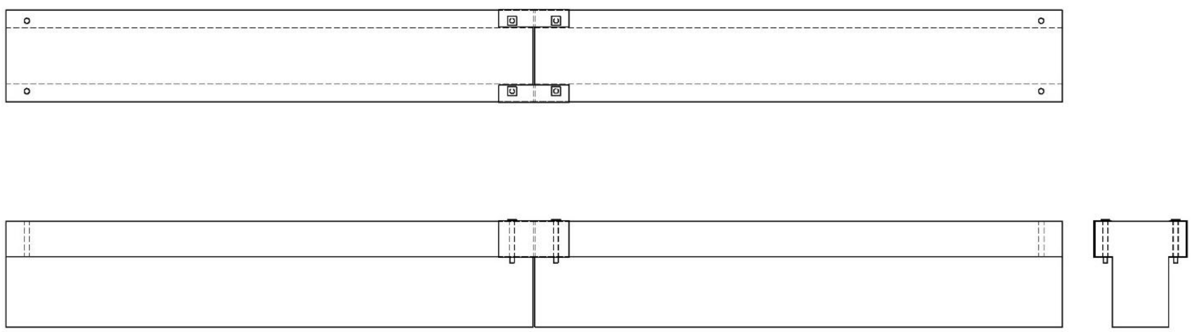


Figure 133. Concept No. 8

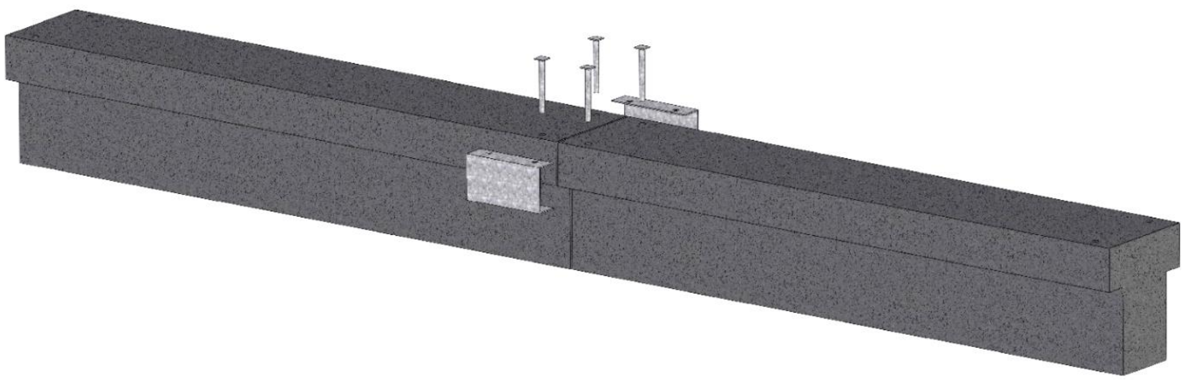


Figure 134. Concept No. 8 Parts

Figure 135. Concept No. 8 Assembly

6.1.9 Concept No. 9

Concept no. 9, as shown in Figure 136, features a vertical shape barrier with a step incorporated into each barrier end, allowing adjacent barriers to overlap. Two pins are dropped vertically through this overlap, joining the barrier sections. The barrier segments could be placed horizontally or vertically. While this concept only required two connection pins for hardware, there were concerns about concentrating the connection loading through a narrow section of the concrete barrier. Special end sections may also be required for this barrier concept due to its irregular barrier end geometry.

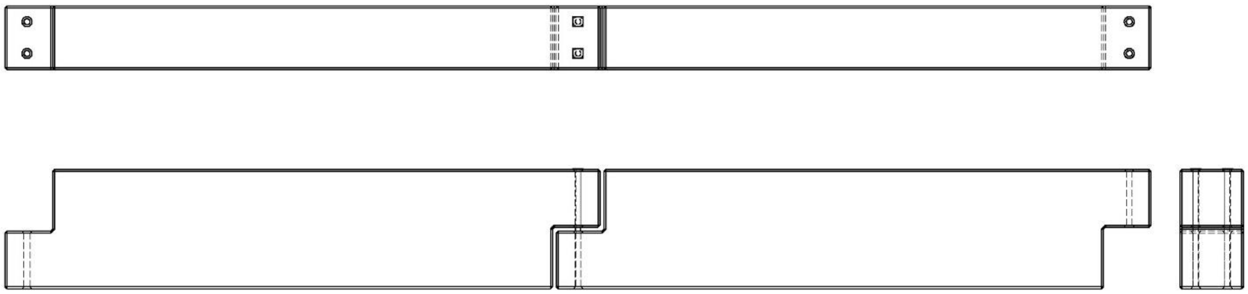


Figure 136. Concept No. 9

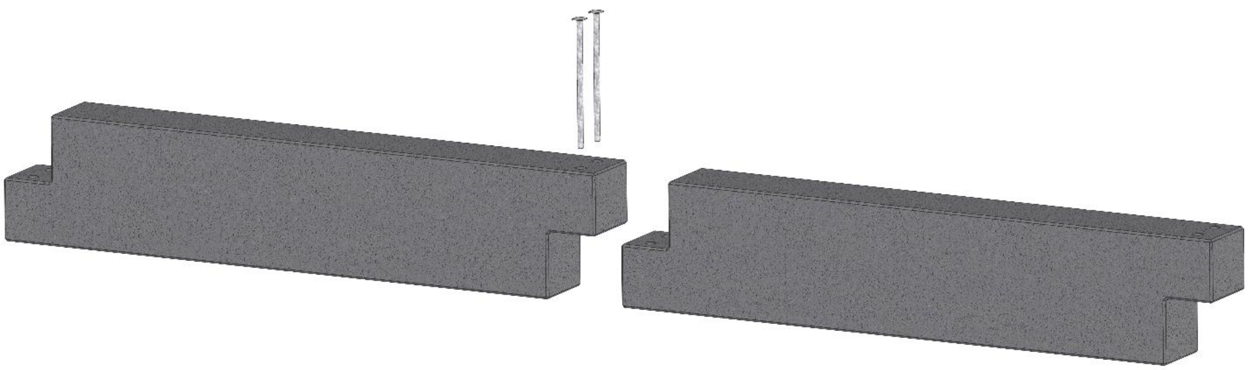


Figure 137. Concept No. 9 Parts

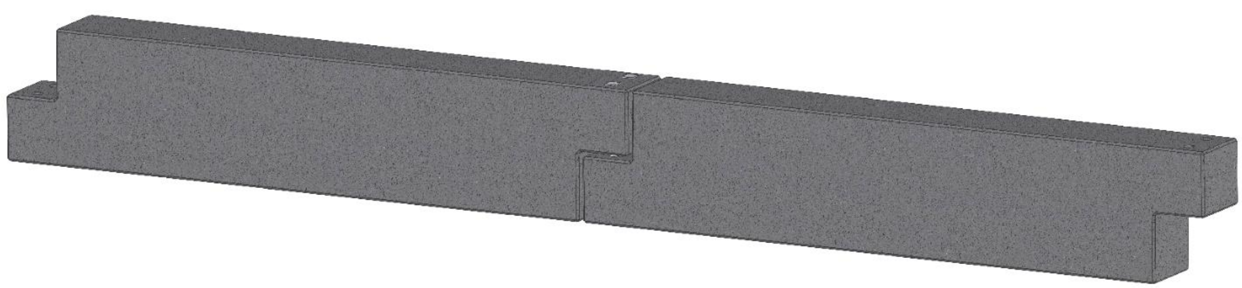


Figure 138. Concept No. 9 Assembly

6.1.10 Concept No. 15

Two versions of concept no. 15 are shown in Figures 139 and 140. These concepts are derivatives of concept nos. 1 and 6 detailed previously. Version no. 1 features a hinge connection with a pin and an extruded and recessed end that fit together. Version no. 2 has two steel plates cast into the barrier on one end. The other barrier end has two recesses cut out which receive the extruding steel plates from adjacent barrier segments. For both versions, a pin is dropped through each barrier end for a total of two pins per barrier segment and one pin per connection joint. Both concepts focused on reducing the number of connection pins in the concepts. However, reducing the number of pins also reduced the moment continuity, which may lead to increased barrier deflections.

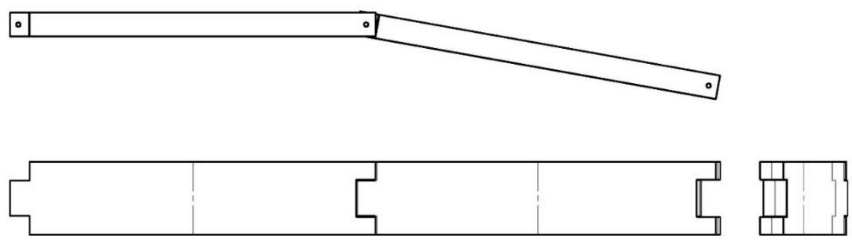


Figure 139. Concept No. 15 Version 1

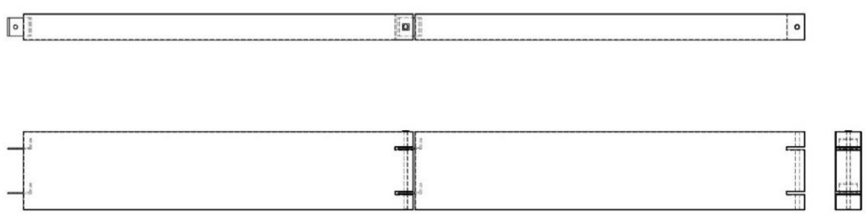


Figure 140. Concept No. 15 Version 2

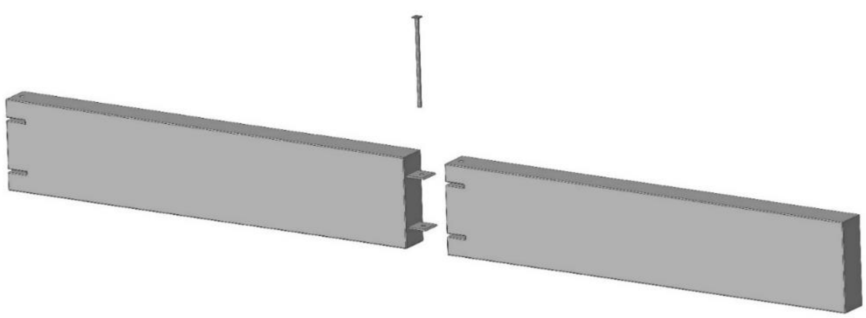


Figure 141. Concept No. 15 Version 2 Parts

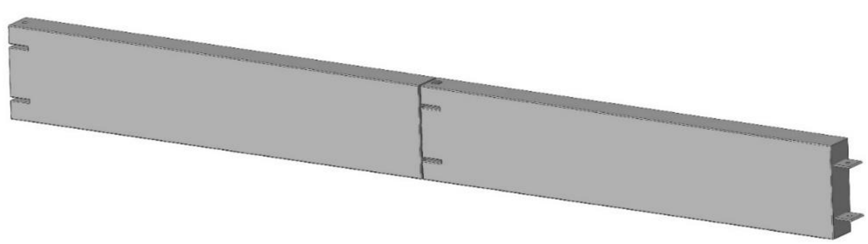


Figure 142. Concept No. 15 Version 2 Assembly

6.1.11 Concept No. 16

Concept no. 16 features short, stackable barrier segment sections which are staggered longitudinally with a ½ barrier length offset, as shown in Figures 143 through 145. One connection pin hole was located at each end of the barrier segment and two connection pin holes were located near the midpoint of the barrier length. Connection pins were dropped through the holes in the barrier segments to connect the longitudinally staggered barrier elements. This connection allows barriers to be placed vertically or horizontally. This connection design was simple and would provide a high degree of moment continuity throughout the barrier. Special end sections may also be required for this barrier concept due to its irregular barrier end geometry.

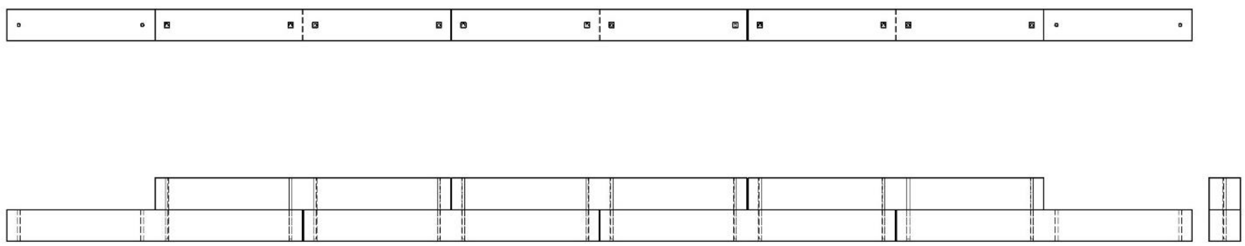


Figure 143. Concept No. 16

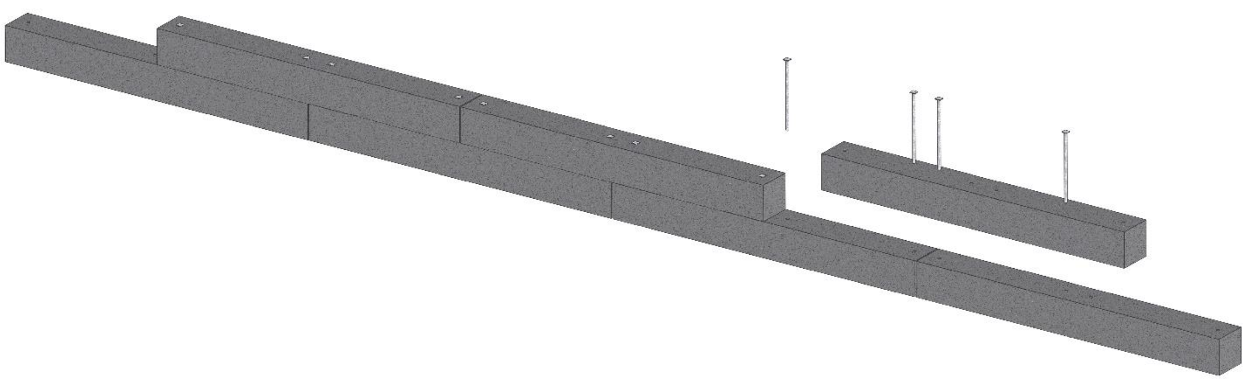


Figure 144. Concept No. 16 Parts

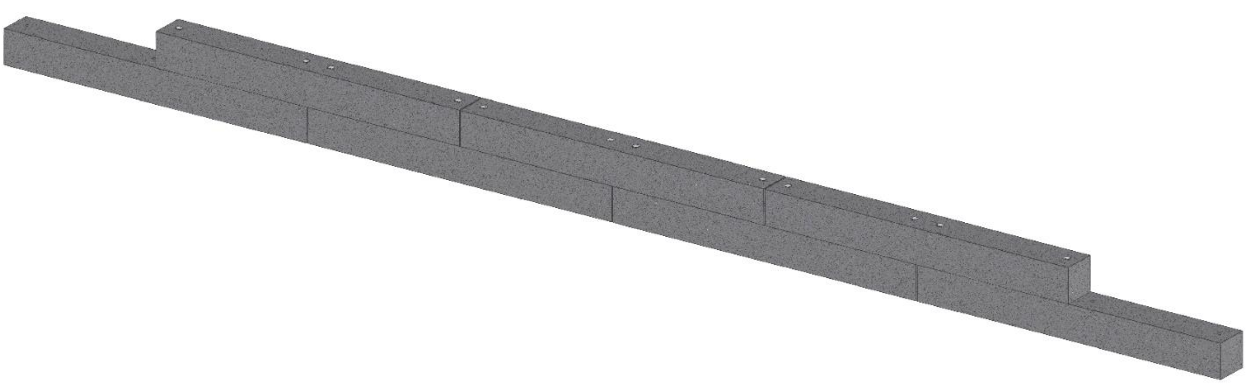


Figure 145. Concepts No. 16 Assembly

6.1.12 Concept No. 17

Concept no. 17 featured a solid concrete barrier segment connected by a single steel base plate assembly, as shown in Figures 146 through 148. The steel base plate assembly would be placed on the roadway and the barrier segments would set on and in the steel base plate assembly, which is shown in Figure 149. No other hardware or tools would be required for installation of this design concept. The primary concern with this concept was that a lack of shear transfer near the top of the barrier segments could allow relative displacement of the barrier segments and increase the potential for vehicle snag at segment joints.

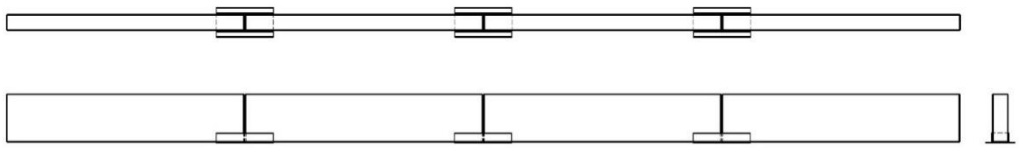


Figure 146. Concept No. 17

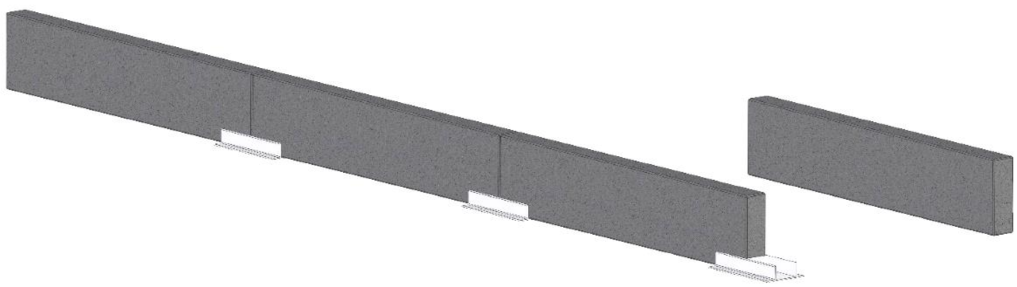


Figure 147. Concept No. 17 Parts

Figure 148. Concept No. 17 Assembly

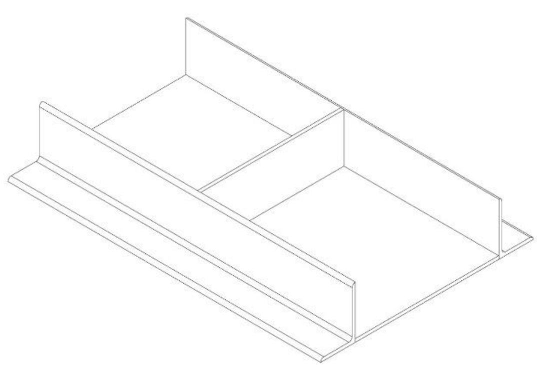


Figure 149. Metal Bracket for Concept No. 17

6.1.13 Concept No. 19

Concept no. 19 consisted of a segmented concrete barrier system comprised of interlocking top and bottom segments that are stacked in an offset or staggered configuration to provide continuity in the barrier without discrete barrier connections or connection hardware between the barrier segments, as shown in Figures 150 through 152. The barrier design concept utilizes upper and lower barrier segments with a fixed length. The lower base segment has a protrusion that extends into an interior cavity in the upper segment of the barrier. The upper and lower segments of the barrier are offset longitudinally ½ of the barrier segment length. The combination of the lower segment inserting into the upper segment and the longitudinal offset effectively interlock the barrier segments to provide moment continuity throughout the barrier system without separate barrier connections. Special end sections may be required for this barrier concept due to its irregular barrier end geometry. It is also believed that this design can be anchored to further reduce deflections using pockets in the lower segment of the barrier that provide a method for installing anchor rods.

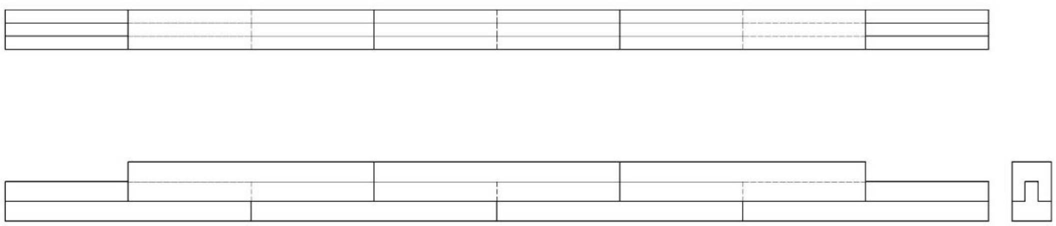


Figure 150. Concept No. 19

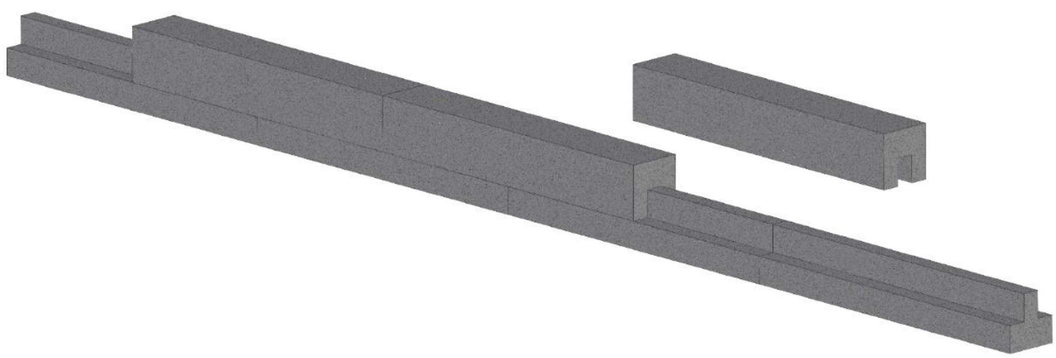


Figure 151. Concept No. 19 Parts

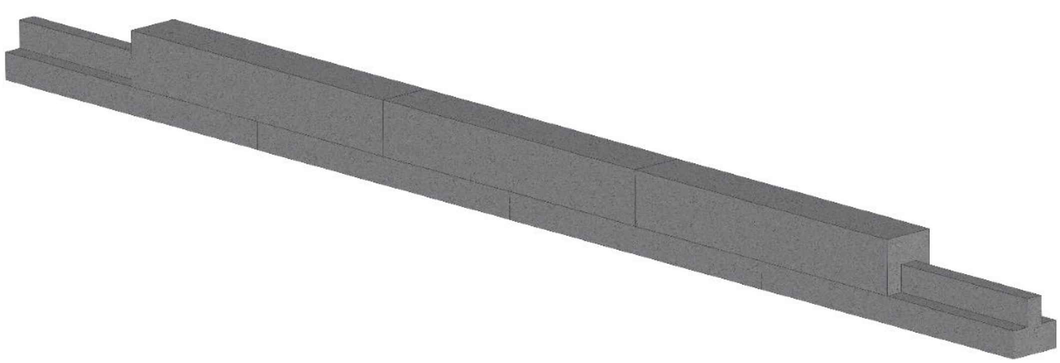


Figure 152. Concept No. 19 Assembly

6.1.14 Concept No. 20

Similar to concept no. 19, concept no. 20 featured stackable sections which are staggered to overlap, as shown in Figures 153 through 155. In this version of the concept, the upper section fits completely over an inner core.

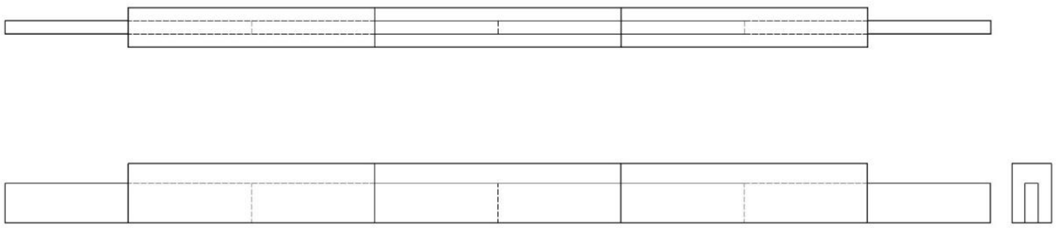


Figure 153. Concept No. 20

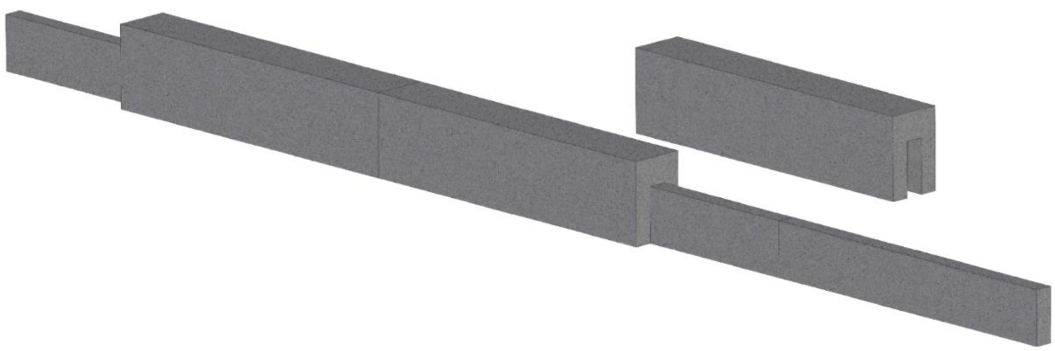


Figure 154. Concept No. 20 Parts

Figure 155. Concept No. 20 Assembly

6.2 Steel Designs

Steel barriers, while more expensive than concrete barriers, have longer service lives than current PCBs. As such, an attempt was made to investigate a potential steel portable barrier concept and estimate potential costs. For the purposes of estimating a potential steel barrier section, an impact load of 65 kips was applied to the barrier segment near the center, and the barrier was evaluated for moment capacity as a simply supported beam. A yield stress of 50 ksi was used for steel. Multiple configurations with overall barrier segment dimensions of 32 in. tall, 16 in. wide, and 12.5 ft long were found which resulted in an acceptable bending capacity.

One issue with steel barriers is that they provide considerably smaller mass compared to concrete barriers of a similar size and a corresponding reduction in inertial resistance. One solution is filling the steel barrier with concrete, but a cavity must be created, as shown in Figure 156. Therefore, configurations which did not result in a cavity were discarded. In addition to the geometry shown in Figure 156, other configurations with cavities were evaluated, including stacked tubes and tubes with sides plates, as shown in Figures 157 and 158. The stacked tubes configuration was made of rectangular tubes welded together. The tubes with side plates concept featured two rectangular tubes welded to sheet steel sidewalls.

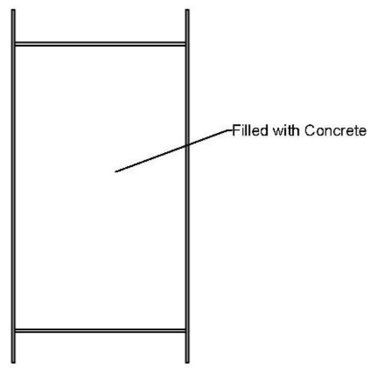


Figure 156. Steel Barrier with Cavity for Concrete Ballast

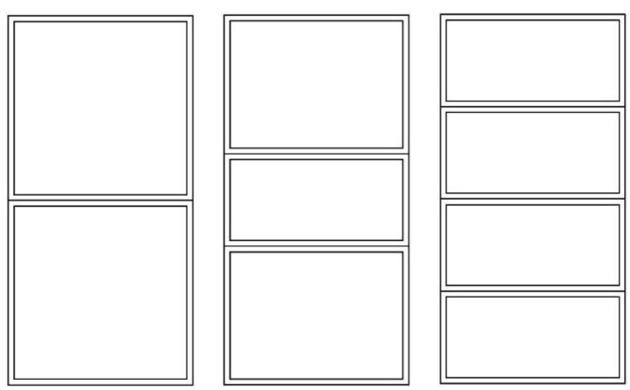


Figure 157. Stacked Tubes Concept

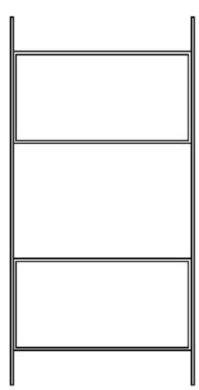


Figure 158. Tubes with Side Plates Concept

Analysis of the various geometries suggested that the tubes with side plates concept provided the best combination of barrier section efficiency, ballasting of the barrier segment, and connection options. A single design concept was developed based on this geometry.

6.2.1 Concept No. 18

Concept no. 18 features a combination of steel and concrete, as shown in Figures 159 through 161. For each barrier segment, two rectangular tubes were welded to two pieces of sheet steel. The pocket formed between the steel pieces was filled with concrete to ballast the barrier section. Two short rectangular tubes telescope into the ends of the barrier segment tubes and pins are dropped through and the barrier segment to connect the barrier segments. This concept used $\frac{1}{8}$-in. thick steel side plates, HSS12x4x$^{3}/_{16}$ tubes for the barrier segment. With the concrete ballast included in the center section of the barrier, the concept weighed approximate 3,540 lb and cost an estimated $250 per linear foot. The concept allowed for vertical or horizontal placement and used a connection with a high degree of moment continuity. However, the low mass and high cost led to concerns about the effectiveness of the design.

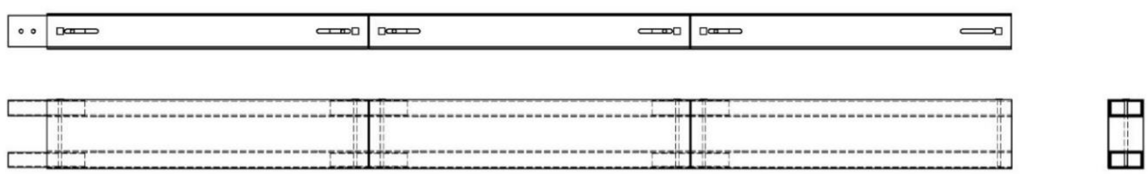


Figure 159. Concept No. 18

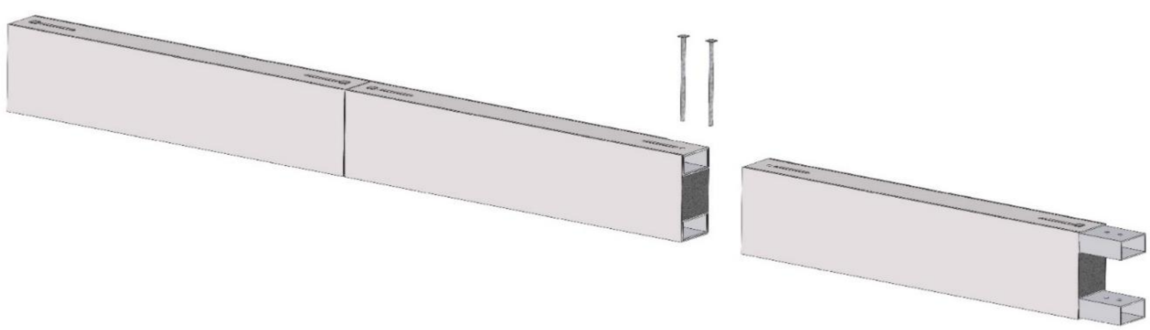


Figure 160. Concept No. 18 Parts

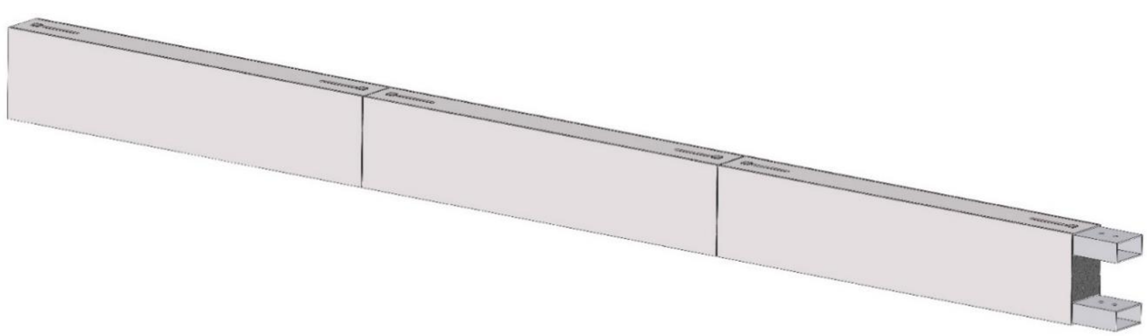


Figure 161. Concept No. 18 Assembly

6.3 Selected Design Concepts

These design concepts were presented to WisDOT and five were selected for additional evaluation and development: concept nos. 1, 2, 17, 18, and 19. These concepts were selected based on their ease of installation and potential for reducing barrier deflection.

The Mid-American Transportation Center (MATC) funded a parallel research project titled *Development of a New Generation of Portable Concrete Barriers* which simulated these selected design concepts under MASH test designation no. 3-11 impact conditions using LS-DYNA. The findings of the MATC study will be fully documented in a parallel project report. A summary of the research approach and its findings are provided in the following chapters due to their relevance to this research effort.

7 LS-DYNA MODEL DEVELOPMENT

The five selected PCB concepts were evaluated in the parallel MATC research effort using LS-DYNA finite element software to evaluate the safety performance and identify possible weaknesses with each design. The simulations for all concepts were compared to each other and to a baseline model of the Midwest F-shape PCB.

Note that for the MATC effort, the five preferred concepts were updated to incorporate the 2.4-degree taper recommended for casting of the concrete barrier segments. Additional minor modifications and updates were made to refine the initial concepts.

7.1 Baseline Model of Midwest F-Shape PCB

A model of the Midwest F-shape PCB was used as a baseline for comparing the concepts. 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 since its creation [82]. 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 also 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 162.

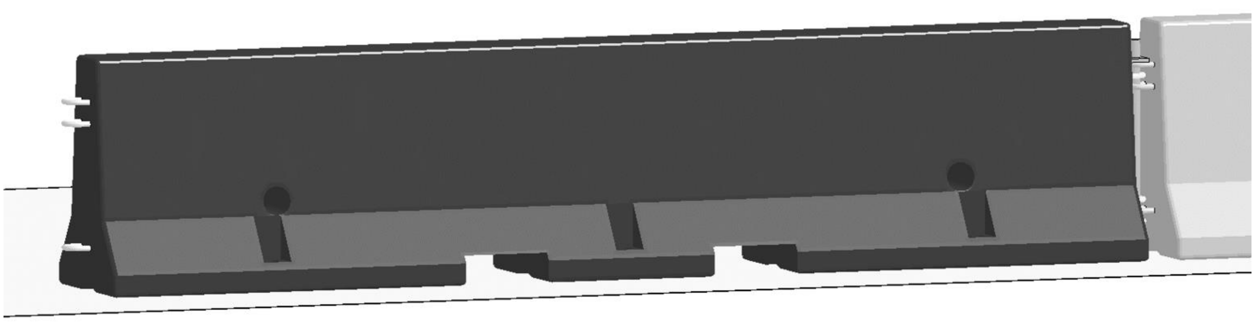


Figure 162. LS-DYNA Baseline Model of F-Shape PCB

The body of the PCB segments were 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 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 is 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 163.

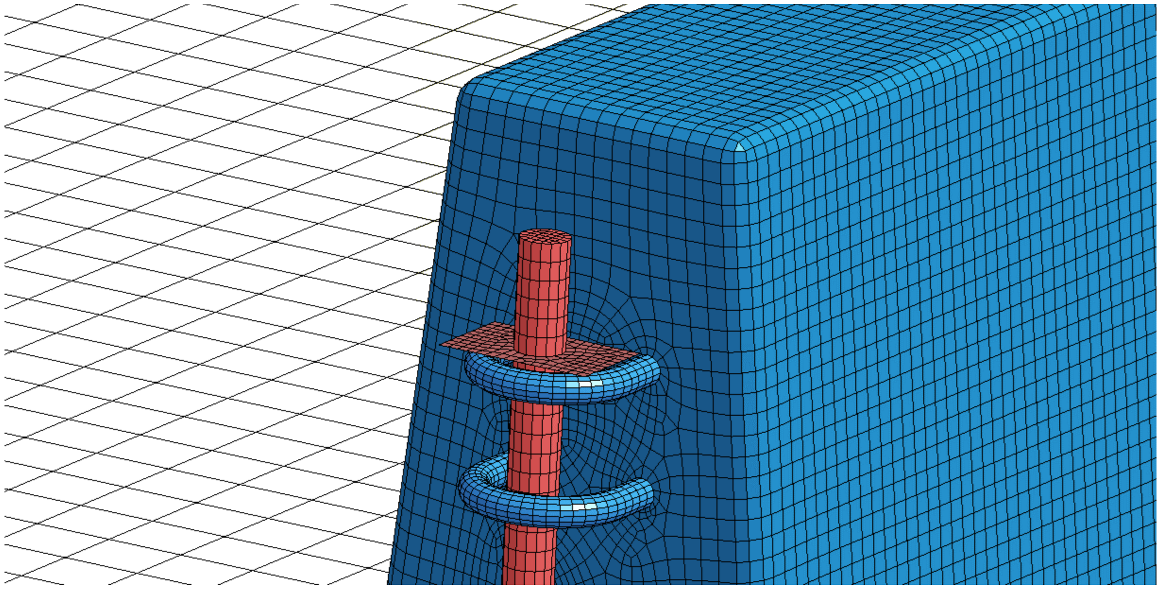


Figure 163. Close-Up View of Element Mesh in Baseline F-Shape Model

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 [15]. This value was assigned to the contact between the ground and the barrier segments within the model. The default friction coefficient for contact between other parts within the barrier model 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.

To avoid initial penetrations between 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 when the simulation began. This introduced vibration caused by 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 that the damping would have no effect on safety performance or barrier 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 segment nos. 8 and 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 [248]. Crash test no. 2214TB-2 conducted as part of this 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 this crash test are compared with the simulation results in Table 58.

Table 58. 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

7.2 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 helped prevent any issues found during the first steps of modeling a concept from carrying over to another. Systematic construction of concept models and a shared numbering system also added to the ease at which models could be replicated to other concepts and shared issues could be identified and corrected quickly across models.

Element types and material models used across each model are provided in Table 59. Note that certain parts are not included in all concepts. For example, part nos. 44, 45, 46, and 47 are only used in the model for concept no. 18. Barrier parts for each concept are shown in figures within the following subsections.

Table 59. Barrier Model Parts, Elements, and Materials

Part Description	Simulation Part No.	Element Type	Material
Concrete Barrier	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.

7.2.1 Concept No. 1

Concept No. 1 consisted of PCB segments that are 12.5 ft long, 32 in. tall, and 16 in. wide at the base with a near-vertical face that is sloped at 2.4 degrees to aid form release during construction. The barrier segments are connected with four 1¼-in. diameter steel pins inserted through the ends of the barrier segments and two steel plates that are 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 was modeled using 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 mass 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 like a rigid wall. The element mesh for connection hardware and barrier segments is shown in Figure 164.

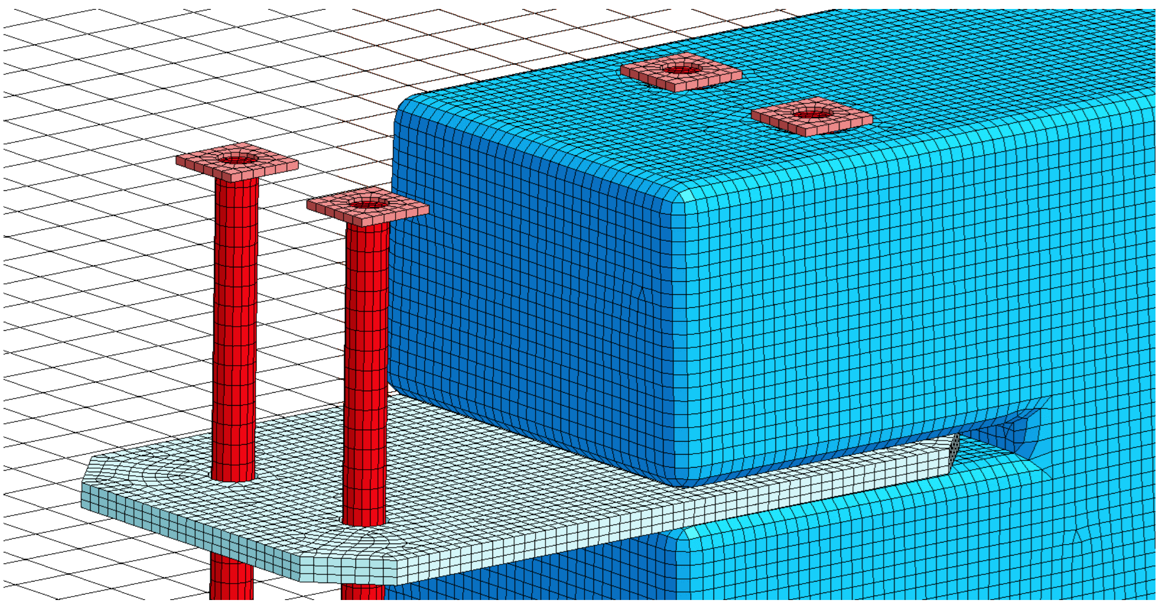
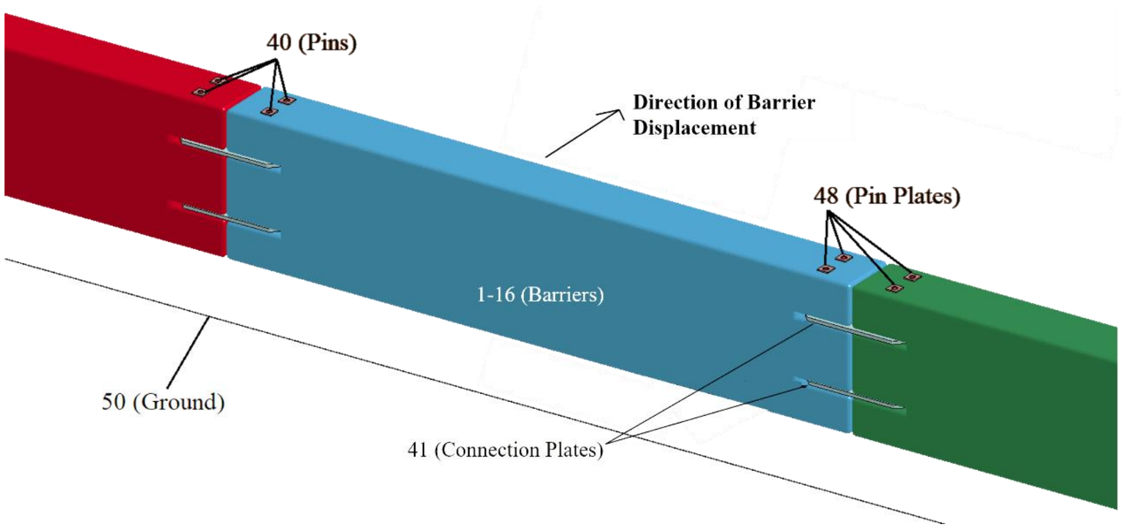
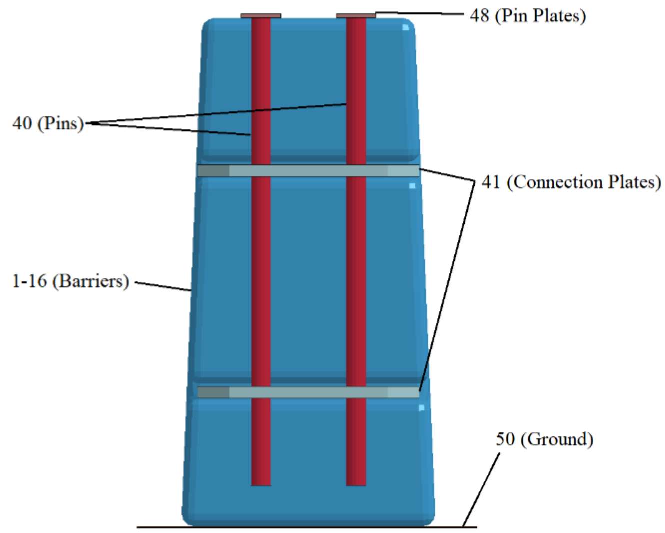


Figure 164. Close-Up of Mesh for Concept No. 1

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 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 were 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 165.



Isometric View



Joint Section View

Figure 165. Concept No. 1 Part Numbers - Isometric View (Top) and Section View (Bottom)

7.2.2 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 is nearly identical to concept no. 1, however concept no. 2 incorporates 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 are included, the total width is 19.15 in. The weight of a single barrier segment is 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 is to provide an easy location for anchoring the barrier, should it be desired in the future, and to improve the stability of the narrower barrier segments. 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 defining elements where the holes were located on the vertical face of the feet to the part for the corresponding barrier segment. 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 close-up view of the mesh of the steel feet brackets is shown in Figure 166.

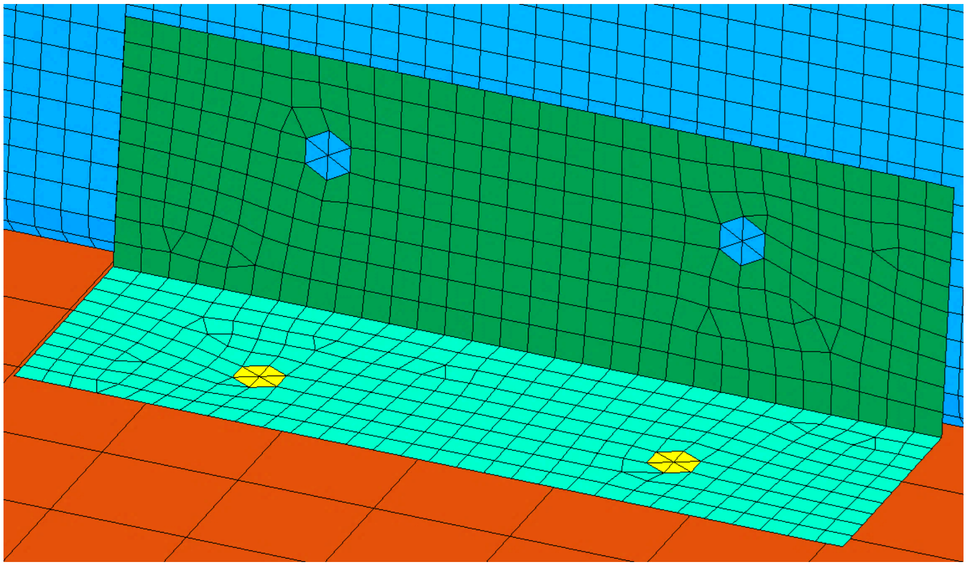


Figure 166. Mesh of Steel Feet Brackets for Concept No. 2

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 total pins per joint was not sufficient to maintain continuity between barrier segments. The discontinuity at the joint directly downstream from impact during the initial simulation is shown in Figure 167. Note that the pickup model is hidden so the translation of the barriers is more easily visible.

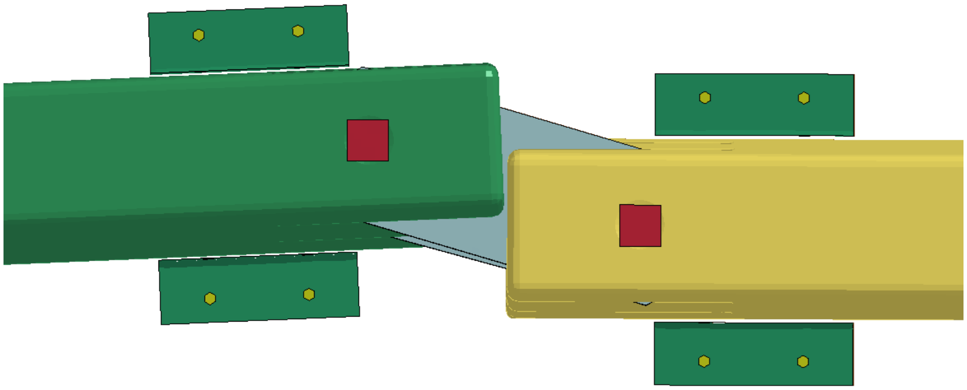
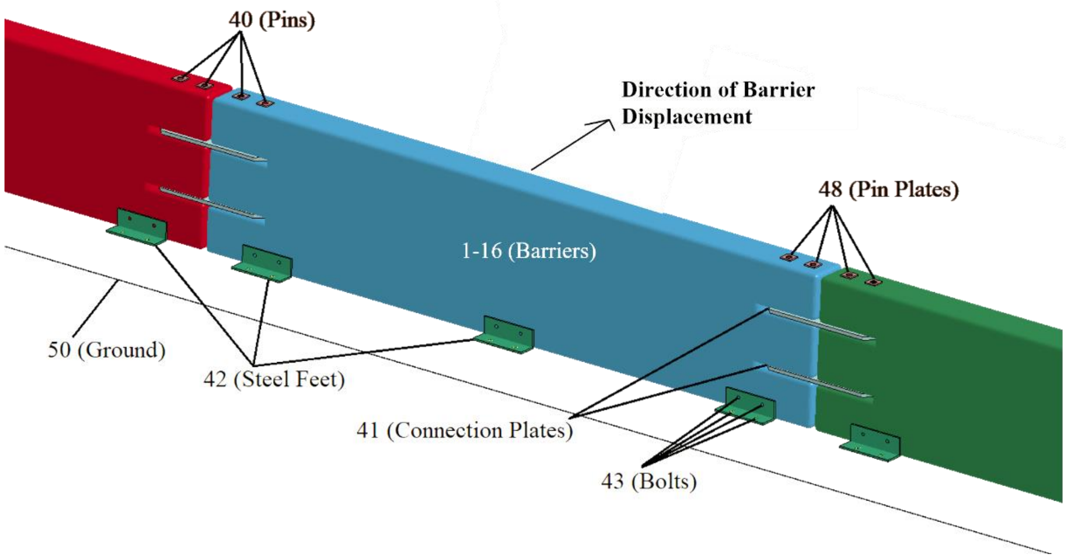
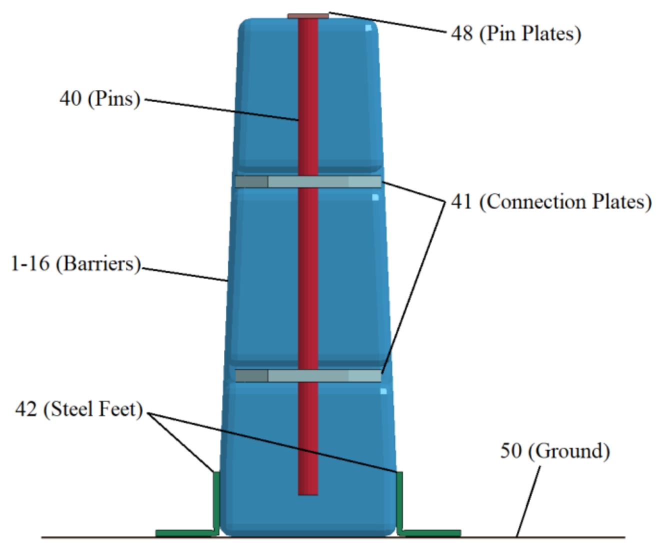


Figure 167. Continuity Issue with Original Connection Design of Concept No. 2

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 that were present in the model for concept no. 2 are shown in Figure 168.



Isometric View



Joint Section View

Figure 168. Concept No. 2 Part Numbers - Isometric View (Top) and Section View (Bottom)

7.2.3 Concept No. 17

Concept no. 17 features similar geometry to concept no. 2, with the primary difference being the connection design. In concept no. 17, barrier segments sit within a steel base plate assembly to transfer forces from impact to adjacent barrier segments. The concrete barrier segments are 11 in. wide, but the steel base plate assembly increases the total width to 19.25 in. Each barrier segment weighs approximately 4,430 lb, or 350 lb/ft, including connection hardware. Since the concrete barrier segments sit on top of the steel feet, the overall height is 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. Concept no. 17, however, only consisted of the concrete barrier segments and the steel base plate assembly located at each joint. Both the barrier segments and feet were modeled with shell elements as they were in previous design concepts. The only major adjustment that was made for this concept was the contact friction between the ground, steel base plate assembly, 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 determined that the steel base plate assembly was not tall or strong enough to restrain the top of the barrier segments from tilting back upon impact and creating a snag opportunity on the next downstream segment. This discontinuity is shown in Figure 169, 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 forward due to inertia as the feet bracket pushed the bottom of the barrier back.

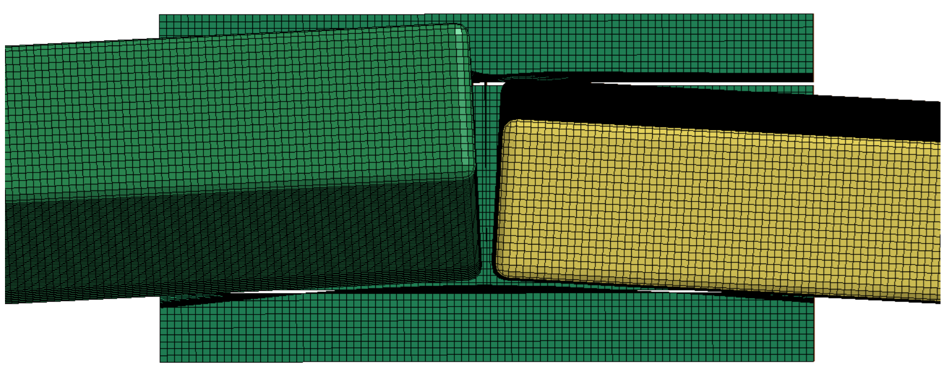
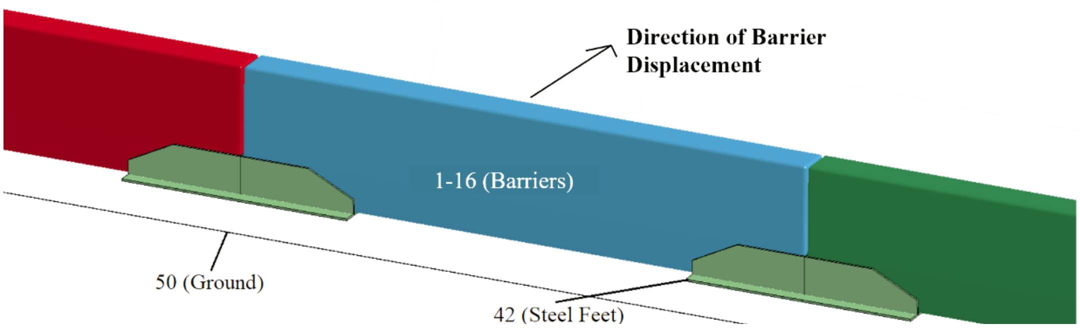


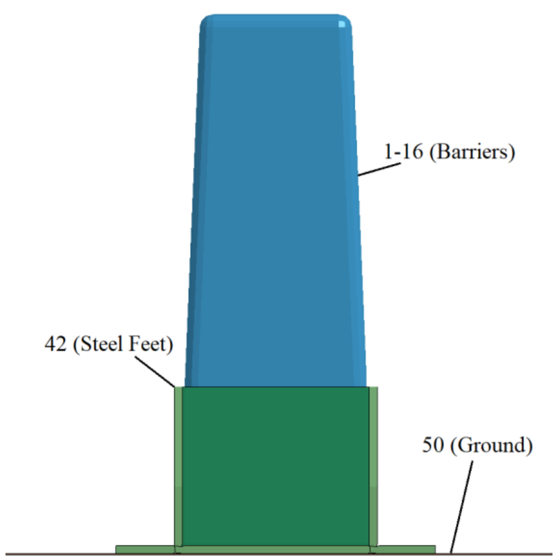
Figure 169. Continuity Issue with Original Feet Brackets in Concept No. 17

The changes implemented to the connection design to alleviate the continuity issues consisted of a revised steel base plate assembly design. The revised steel base plate assembly was 60 in. long, 19.25 in. wide, 10 in. tall, and would be built up from welded plates that are ½ in. thick, except for the vertical center plate which is ⅜ in. thick. This was a significant increase from the original steel base plate assembly that was 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 revised steel base plate assembly still demonstrated enough discontinuity to snag the vehicle and terminate the simulations. 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, allowed the simulation impact model to run to completion. Although this would not result in a truly direct comparison due to impacting the barrier farther upstream from the joint compared to the other concepts, the simulation with impact at the altered location was used for comparison to the other PCB concepts. Results from the simulation of concept no. 17 with the altered impact point still demonstrated poor continuity and load transfer between barrier segments and excessive vehicle snag on the barrier joint. It was determined that this concept would need significant modification to create a viable design, so no further investigation into this concept was conducted. The barrier parts for concept no. 17 are labelled in Figure 170.



Isometric View

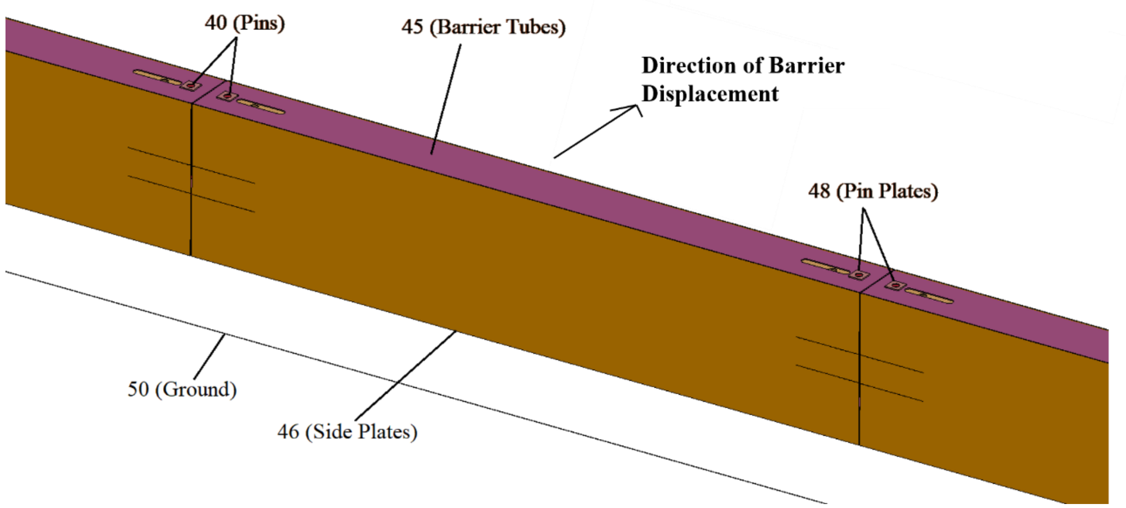


Joint Section View

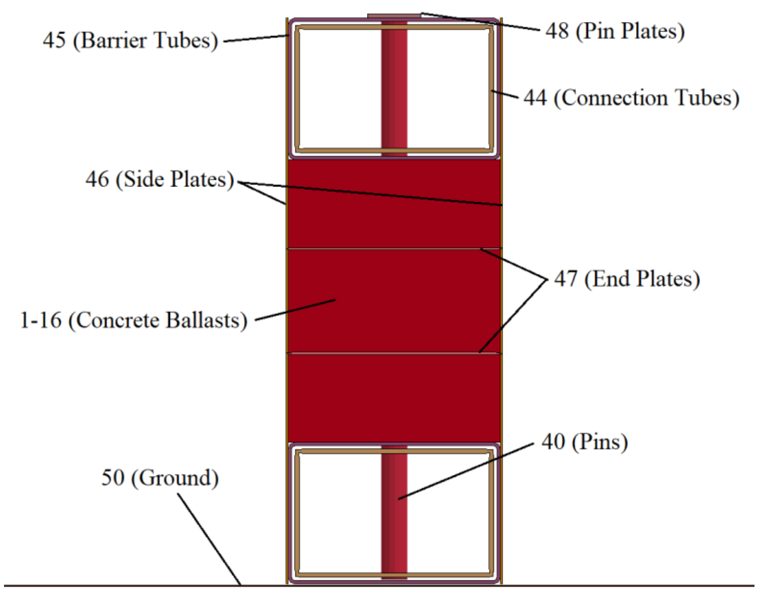
Figure 170. Concept No. 17 Part Numbers - Isometric View (Top) and Section View (Bottom)

7.2.4 Concept No. 18

Concept no. 18 is unlike the other PCB concepts, in that it consists of barrier segments with vertical faces and uses steel as the primary material. Concept No. 18 consists of two steel plates and two rectangular HSS tubes encasing a concrete ballast that is kept in place by small steel plates at either end of the barrier segment. The segments are connected using rectangular HSS tubes that nest inside the HSS at the top and bottom of the barrier segments. The nested HSS tubes are connected using 1.5-in. diameter steel connection pins, similar to the 1.25-in. steel pins used in the previous PCB concepts. Each barrier segment measures 12.25 in. wide, 32 in. tall, 12.5 ft long, and weighs approximately 3,140 lb, or 250 lb/ft. Concept No. 18 is shown with parts labeled in Figure 171.



Isometric View



Joint Section View

Figure 171. Concept No. 18 Part Numbers - 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 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 those parts.

The concrete ballasts were modeled using solid elements with a rigid material definition. Solid elements were used so that damage to the concrete ballast could be investigated 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 all the parts in concept no. 18 are shown in Figure 172.

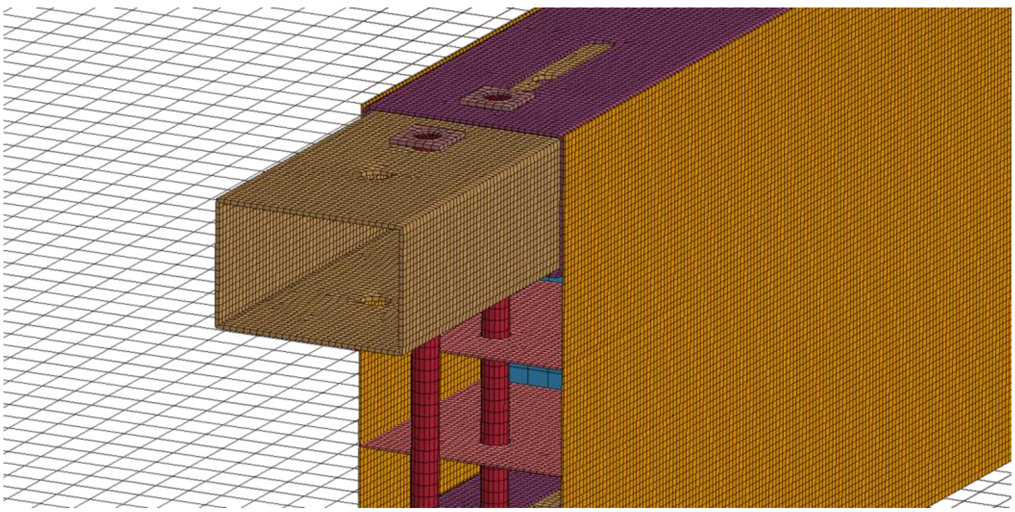
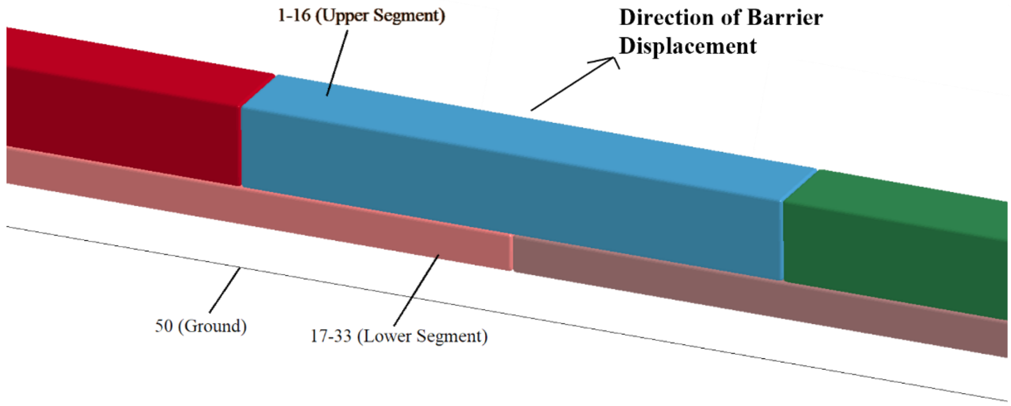


Figure 172. Close-up of Mesh of Concept No. 18

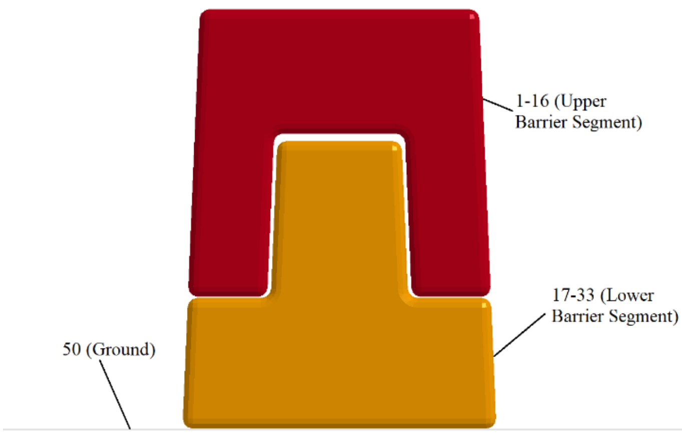
7.2.5 Concept No. 19

Concept no. 19 consists of staggered halves of PCB segments that interlock when stacked on top of each other. The bottom half of the barrier is shaped like an inverted T, and the top half is shaped like an inverted U. When the top halves are stacked on top and staggered at half of the length of the barrier segments, the barrier segment interlock and create 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.

\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, just like the other models. Contact between the PCB sections and the ground was defined with automatic single surface contact to provide appropriate barrier to ground friction, and a separate contact was defined for 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 with the model parts labeled in are shown in Figure 173 and Figure 174.



Isometric View



Joint Section View

Figure 173. Concept No. 19 Part Numbers - Isometric View (Top) and Section View (Bottom)

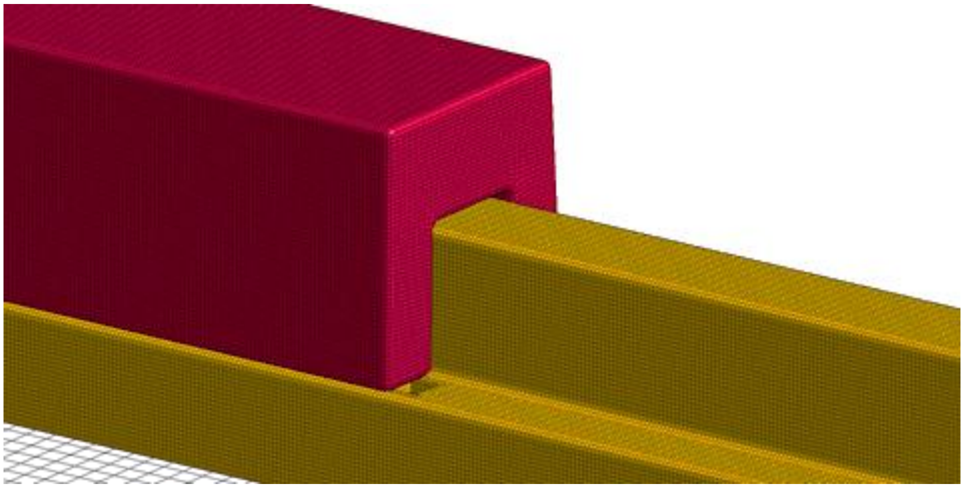
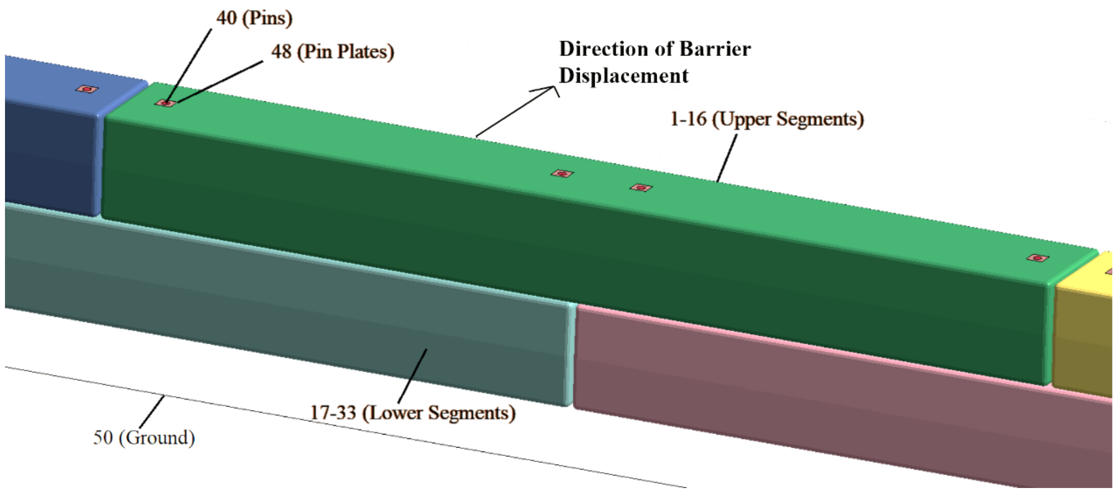


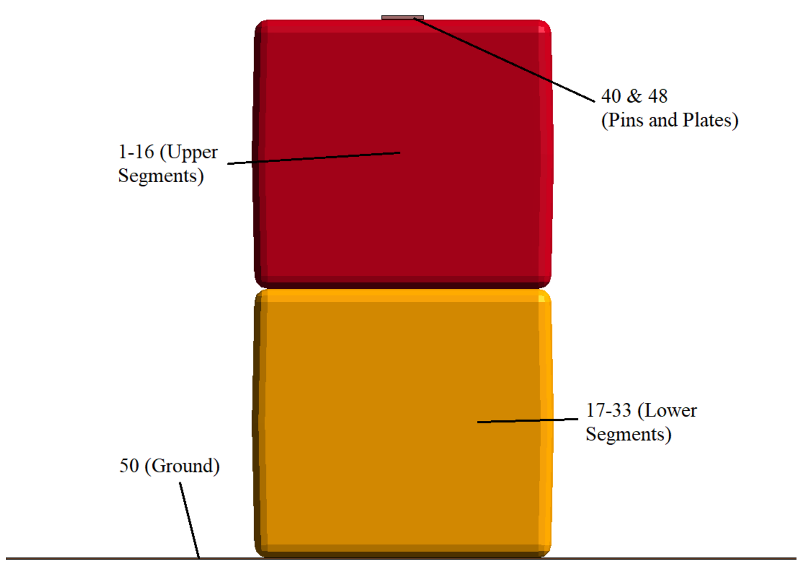
Figure 174. Meshed View of Concept No. 19

7.2.1 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, consists of staggered concrete blocks, similar to concept no. 19, except instead of using interlocking shapes, concept no. 16 uses 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 have 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 175.



Isometric View



Joint Section View

Figure 175. Concept No. 16 Part Numbers - 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, just as in 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 close up of the mesh used for concept no. 16 is shown in Figure 176.

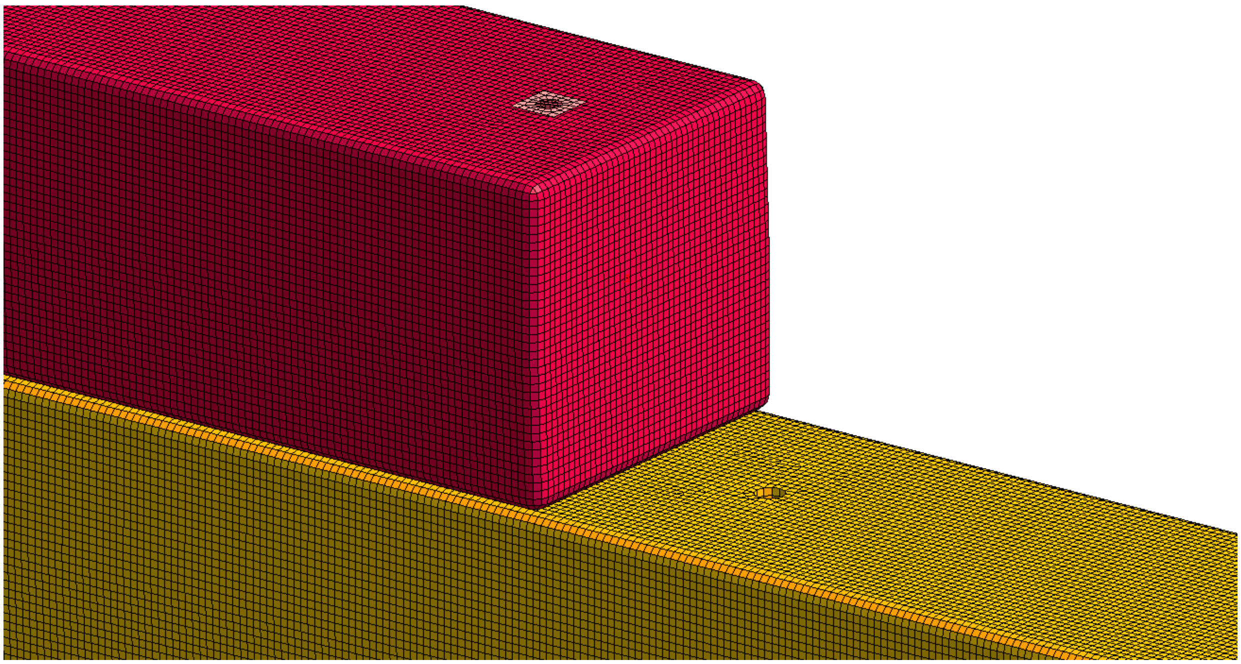


Figure 176. Meshed View of Concept No. 16

8 LS-DYNA PCB CONCEPT MODEL RESULTS

Multiple simulations were run for each design concept so that modeling errors and issues could be corrected and later to investigate slight modifications to each concept. Each simulation was conducted to match MASH test 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 were 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 of the central PCB joint, and for concepts with staggered segments, the impact point was 51.2 in. upstream of the central joint in the upper segments.

A limited discussion of the simulation results is provided in the following sections. Full details on the simulation analysis were provided in the summary report for the parallel MATC research project titled *Development of a New Generation of Portable Concrete Barriers* [249].

8.1 Simulation of Baseline F-shape PCB

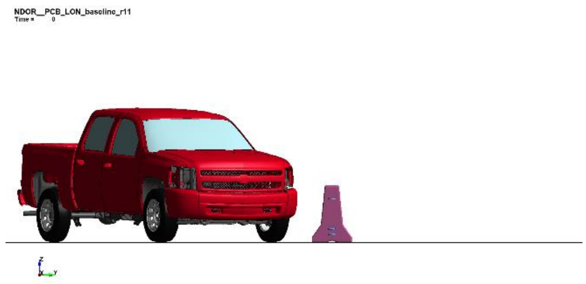
The simulation model of the F-Shape PCB previous evaluated to MASH TL-3 served as a baseline of the various PCB concepts. This F-shape barrier consisted of 12.5 ft. long segments that measured 22.5 in. wide by 32 in. tall, and has a linear weight of approximately 400 lb/ft. This barrier data is tabulated in Table 60. Although previous simulation results did exist 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 no. 3-11 simulation are tabulated below in Table 61, and sequential images from the simulation are shown in Figure 177.

Table 60. 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 61. Baseline F-Shape Simulation Results

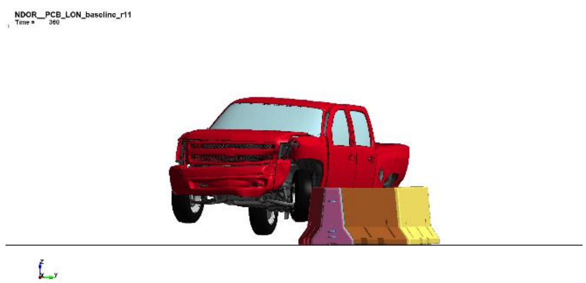
Evaluation Criteria		**Simulation Results**
Max. Vehicle Roll (deg)		15.8
Max. Vehicle Pitch (deg)		20.2
Max. Bumper Climb (in.)		16.9
OIV (ft/s)	Longitudinal	17.3
	Lateral	17.8
ORA (g's)	Longitudinal	7.6
	Lateral	12.7
Barrier Knee Angle (deg)		22.6
Maximum Lateral Dynamic Barrier Deflection (in.)		79.5



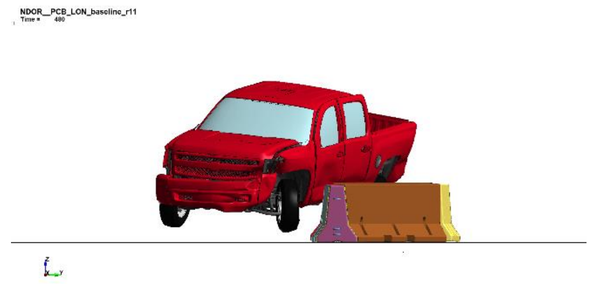
(0 ms)

(120 ms)

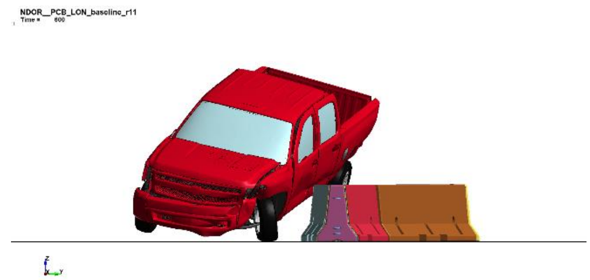
(240 ms)



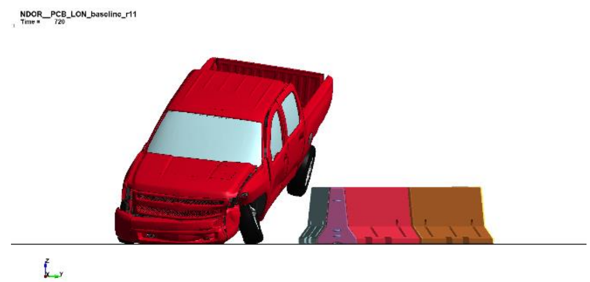
(360 ms)



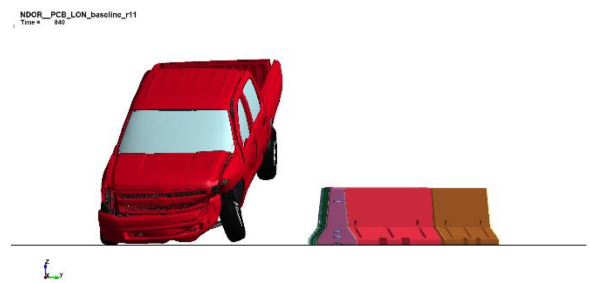
(480 ms)



(600 ms)



(720 ms)



(840 ms)

Figure 177. Sequential Views of Baseline F-shape Simulation

8.2 Simulation of Concept No. 1

The first successful simulation of concept no. 1 featured the PCB design that was described in the earlier section and measured 16 in. wide by 32 in. tall and had a linear weight of about 480 lb/ft. These details are tabulated in Table 62. 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 saw a maximum lateral barrier displacement of 35.1 in. and did not exceed any MASH safety criteria. Detailed results of the concept no. 1A simulation are tabulated in Table 63 and followed by sequential views in Figure 178.

Table 62. Concept No. 1A 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 63. Concept No. 1A 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

Figure 178. Sequential Views of Concept No. 1A Simulation

A modified version of concept no. 1A, labelled concept no. 1B, was developed and utilized a longitudinal pin arrangement instead of a lateral pin arrangement as used in concept no. 2, as shown in Figure 179. Concept no. 1B was simulated to MASH test no. 3-11 and the results were within roughly 5% 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 64.

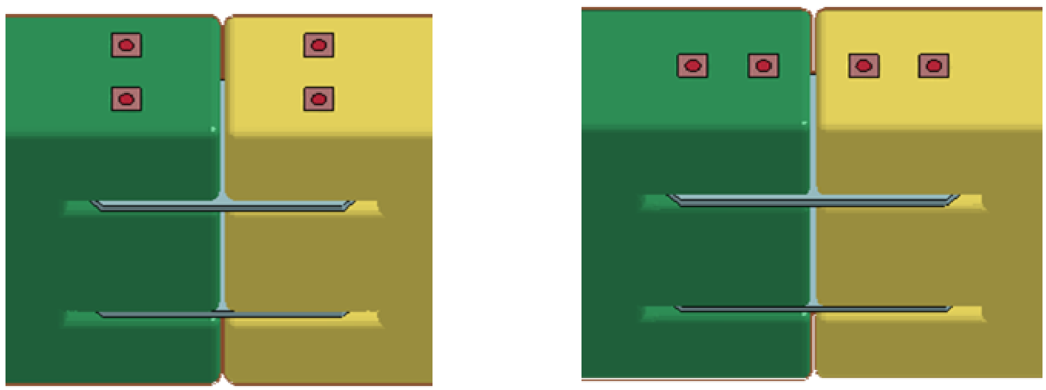


Figure 179. Concept No. 1 Pin Arrangements

Table 64. 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 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. Since the performance of the two versions of concept no. 1 was nearly identical, but the concept no. 1A deflection was more favorable, the decision was made to move forward 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, weighing in at nearly 6,000 lb, which aided in reducing barrier deflection along with the improved joint connection. Since concept no. 1 performed acceptably, it was recommended as a viable concept design.

8.3 Simulation of Concept No. 2

Concept no. 2 was similar to concept no. 1B but incorporated a slimmer width and steel feet at the bottom of the barrier to provide stability. These changes to the design were made in an attempt to evaluate the basic configuration of concept no. 1B while reducing the barrier weight. Concept no. 2 was 11 in. wide by 32 in. tall, and weighed approximately 340 lb/ft. These details are provided in Table 65, below. 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 66, and sequential images from the simulation are shown in Figure 180. Due to the excessive barrier deflection compared to the design goal and that of concept no. 1, concept no. 2 was not recommended as a viable concept design.

Table 65. 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 66. 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

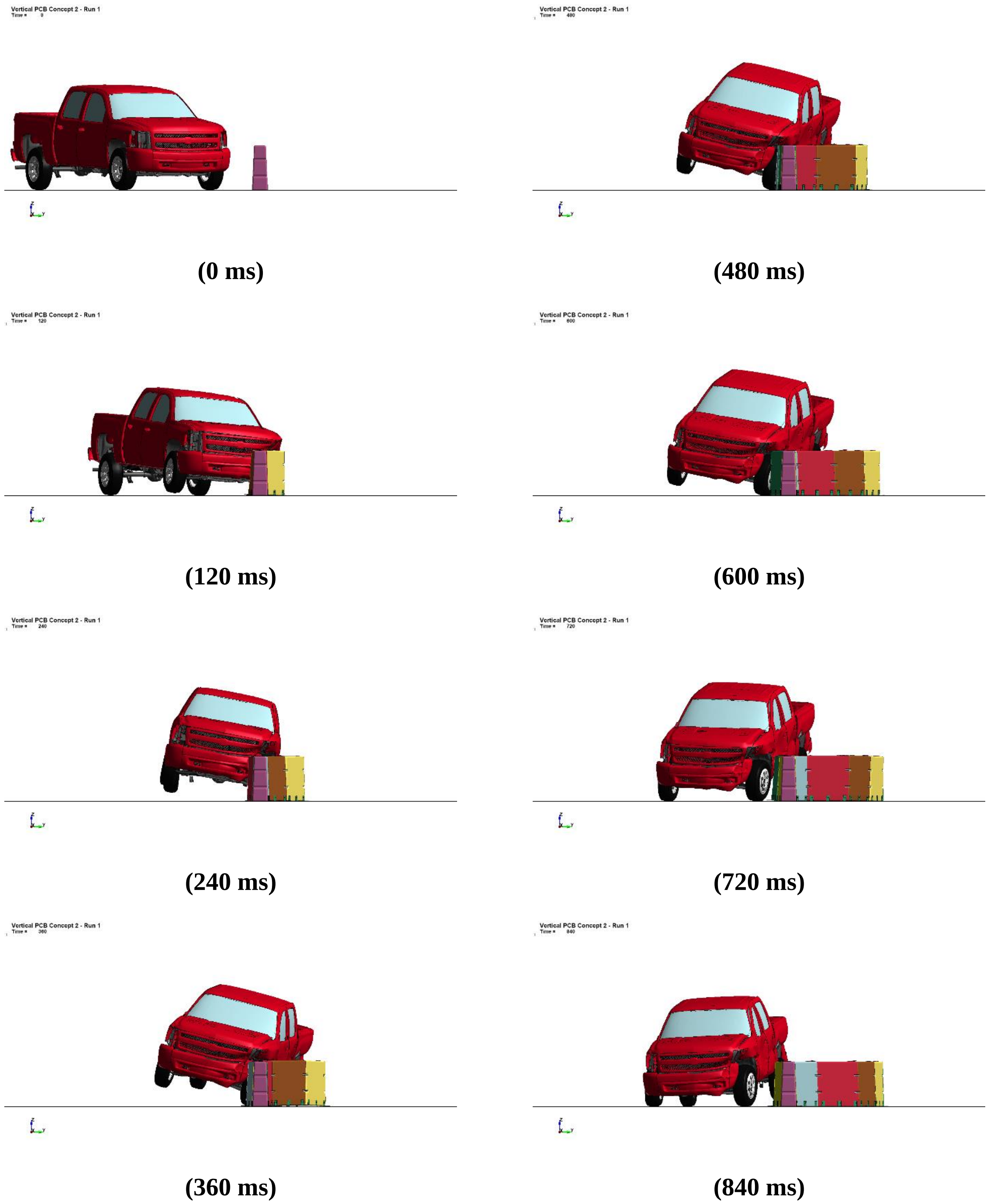


Figure 180. Sequential Views of Concept No. 2 Simulation

8.4 Simulation of Concept No. 17

Concept no. 17 consisted of barrier segments that were the same size as concept no. 2, except they were set into steel feet that spanned the joint between segments. This PCB concept was aimed at simplifying installation and inspection. The dimensions and weights for concept no. 17 are listed in Table 67. This concept was slightly lighter than the F-shape, and was expected to be easy to reinforce, anchor, and add drainage slots in future design phases.

Table 67. 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 initial simulation for concept no. 17 terminated due to errors caused by vehicle snag at the first joint downstream from impact. Since this concept does not have a connection that can transfer shear at the top of the barrier segments, the impacted barrier segment was tipping 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 181.

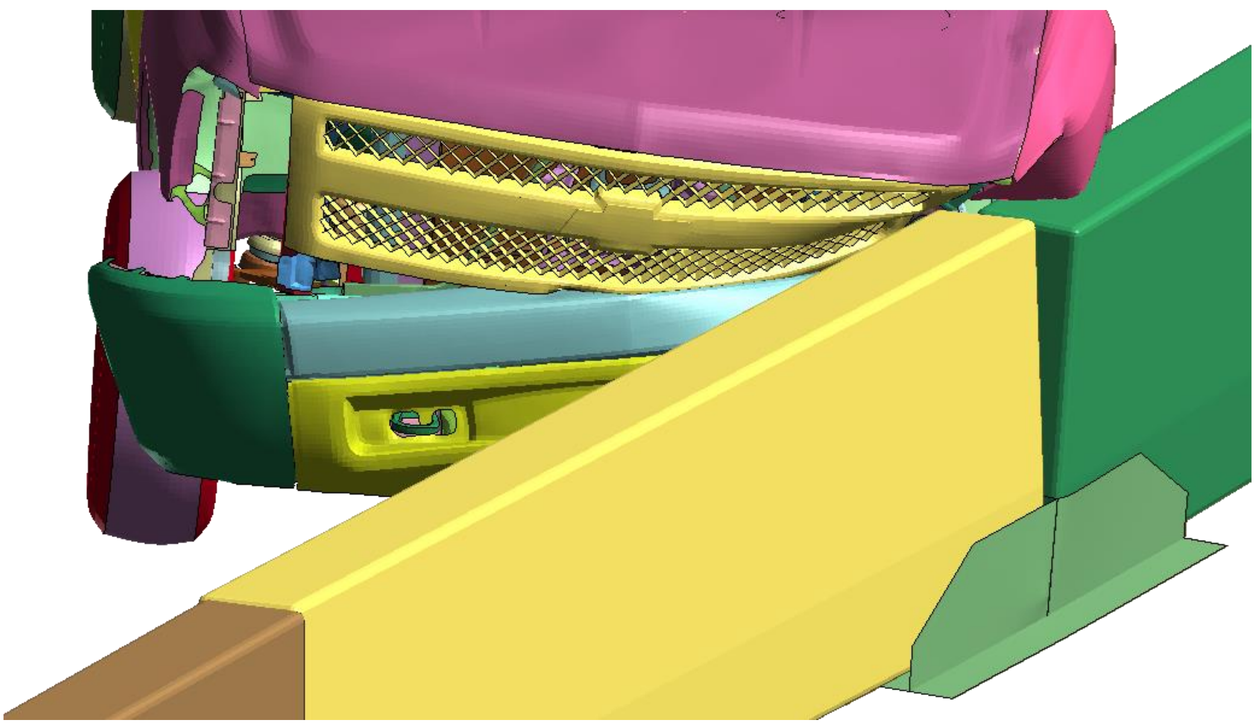


Figure 181. Concept No. 17 Snag Opportunity at Standard Impact Point

To further evaluate the severity of this issue with the design, 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 mitigate the vehicle snag, and the simulation terminated due to errors.

A third impact location at three quarters of a barrier length, or 112.5 in. upstream of the joint was also tested to check for vehicle snag. This impact location still had a small amount of vehicle snag due to barrier discontinuity, but the simulation did not terminate early due to errors. Since the simulation completed, safety criteria were evaluated and showed that the concept nearly reached the maximum MASH limit for lateral occupant ridedown acceleration, 20.49 g. The safety criteria and barrier deflection are listed in Table 68 and sequential images from the simulation are shown in Figure 182. 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 concept design.

Table 68. 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

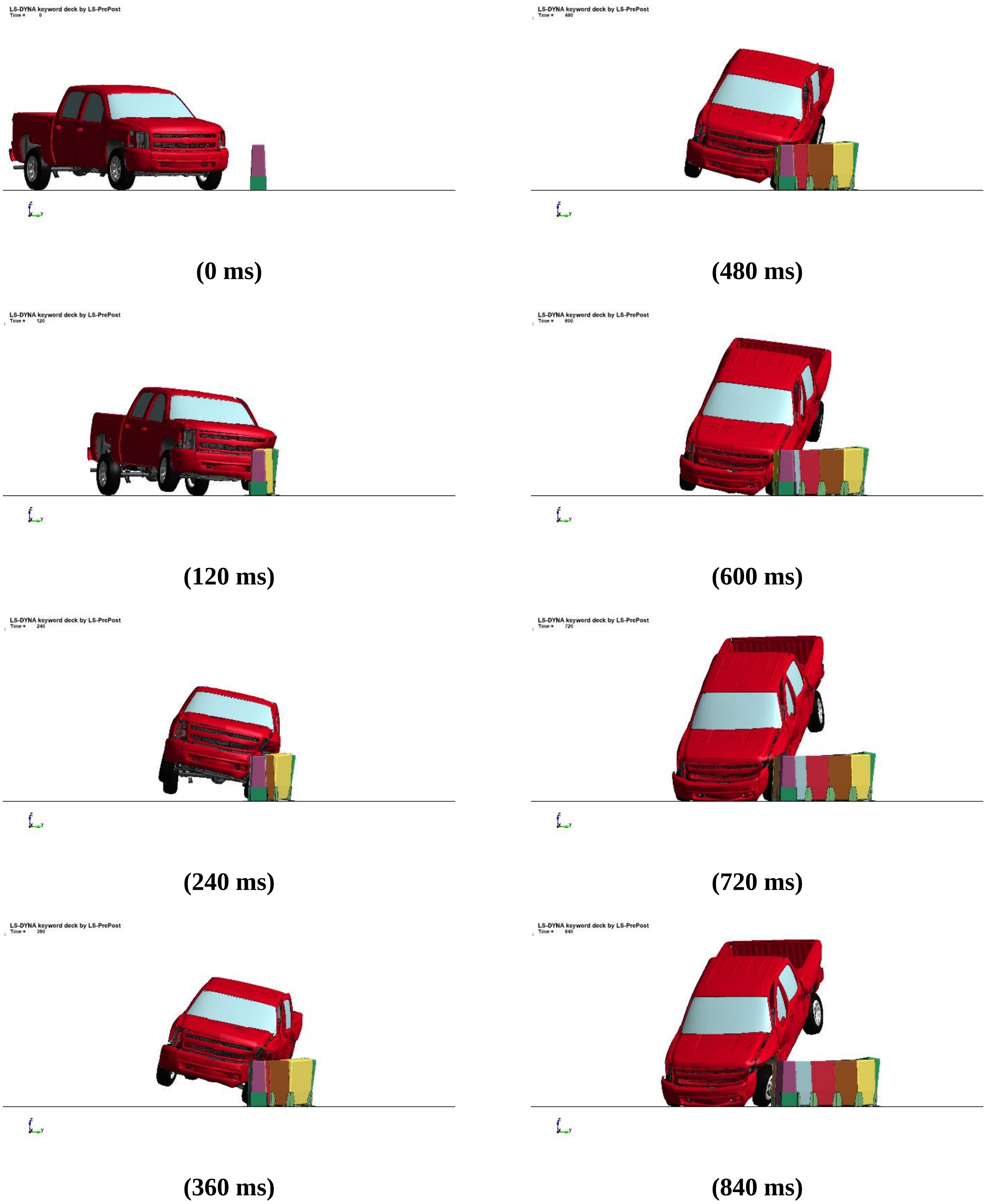


Figure 182. Sequential Views of Concept No. 17 Simulation

8.5 Simulation of Concept No. 18

Concept no. 18 was the only concept selected to evaluate the performance of 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 that the steel face was expected to decrease damage due to impact 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 69, below.

Table 69. 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, however, the maximum lateral barrier displacement was 67.1 in., far exceeding the design goal of 36 in. The simulation results are provided in Table 70, and sequential images from the simulation are shown in Figure 183. 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 concept design.

Table 70. 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

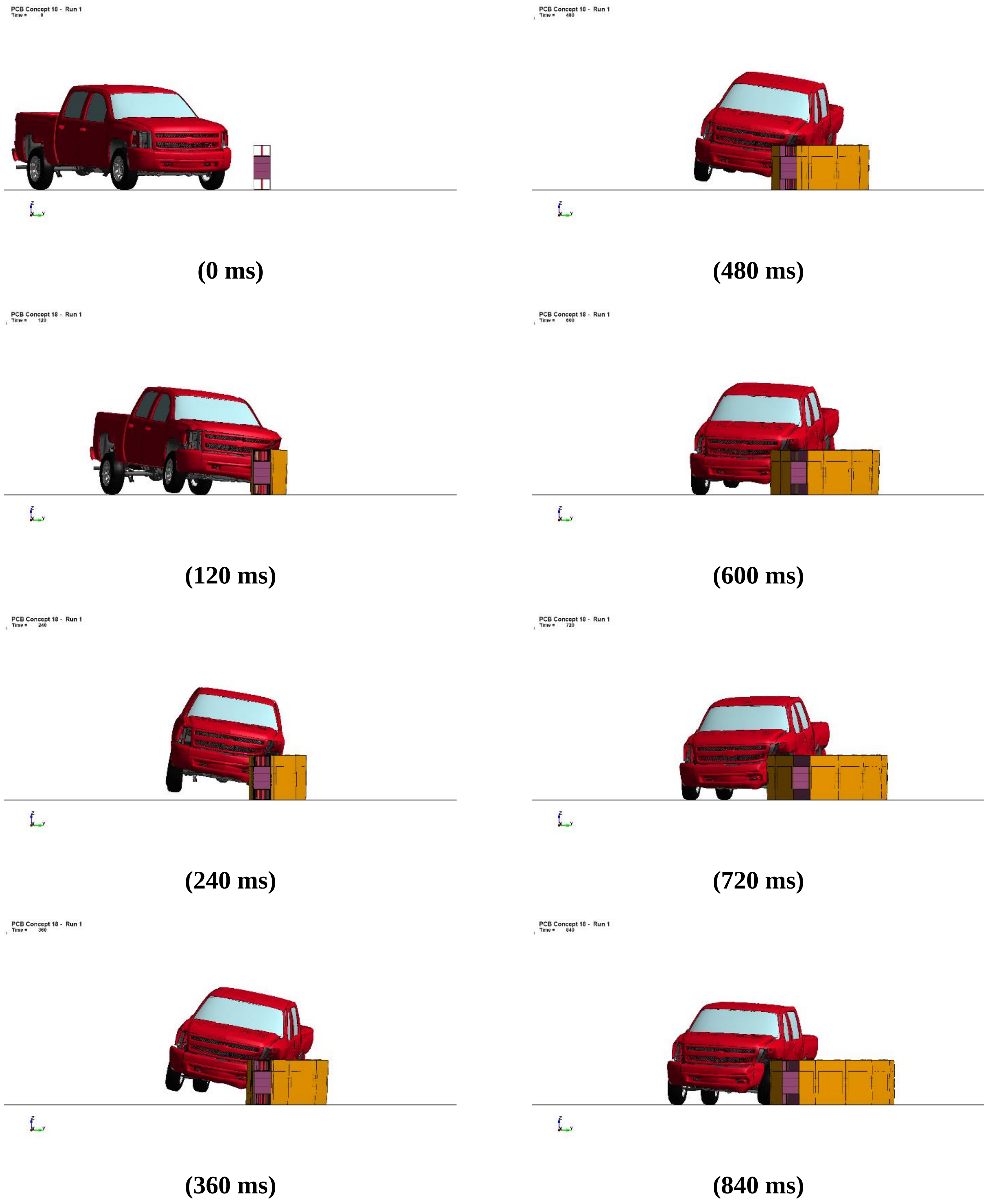


Figure 183. Sequential Views of Concept No. 18 Simulation

8.6 Simulation of Concept No. 19

Concept no. 19 was aimed at simplifying the installation and inspection process by consisting only of concrete barrier segments and no connection hardware. The barrier segments were connected by simply staggering the placement of the top and bottom barrier 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 measurements are listed in Table 71.

Table 71. 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 include the low cost due to the elimination of connection hardware, and the ease at which drainage, lifting points, and anchorage could be implemented. The disadvantages were that the barrier requires two casting shapes, unique end sections to fill the half-segment gap due to the staggered segments, and the weight of the barrier from the large width needed to fit reinforcement. Concept 19A resulted in acceptable safety criteria, and a maximum barrier displacement of 8.4 in. The simulation results are provided in Table 72, and the sequential images from the simulation are shown in Figure 184.

Table 72. 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

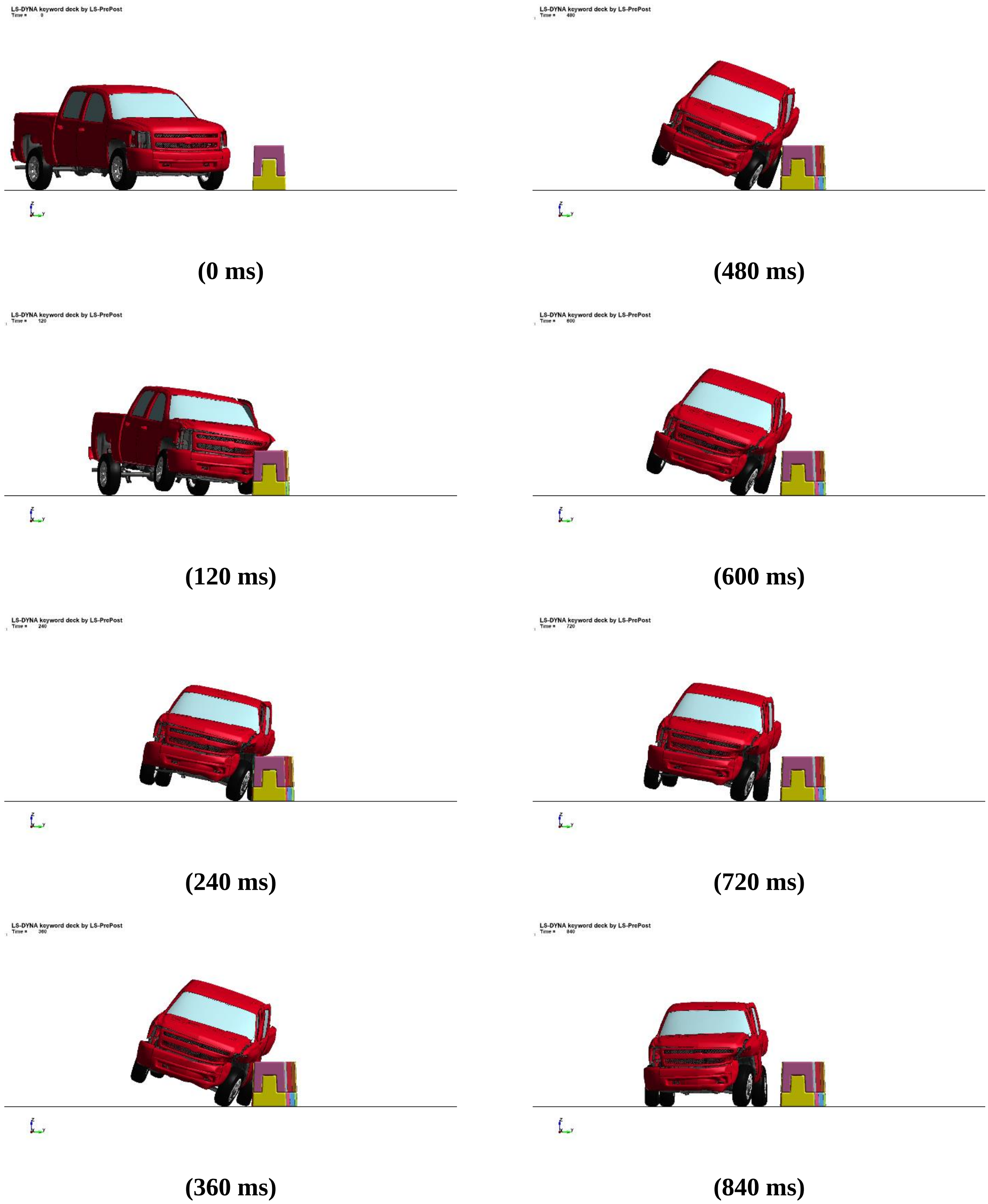


Figure 184. Sequential Views of Concept No. 19A Simulation

After review of the simulation results from the initial configuration of the concept, 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 weight, accommodation of horizontal curvature, and the slope of the barrier face. Concept no. 19B featured an inverted slope in an attempt to further decrease bumper climb and vehicle roll. Concept no. 19C featured a tapered lower barrier stub shape and consistent stub and upper barrier side wall widths to allow for easier reinforcement and barrier assembly. 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 that would allow for increased barrier curvature allowance. 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 3/8 in. in order to balance construction tolerance and the expected barrier deflection due to extra movement resulting from a larger gap. Concept no. 19E consisted of the same cross-section as concept no. 19D, except it used 8-ft segment lengths compared to 12.5-ft segments. Concept 19F used the same 18-in. width and 8-ft segments as concept no. 19E, but featured a shortened stub in an attempt to reduce the reinforcement needed in the connecting stubs of the barrier. The different versions of concept no. 19 are shown in Figure 185, and details are provided in Table 73.

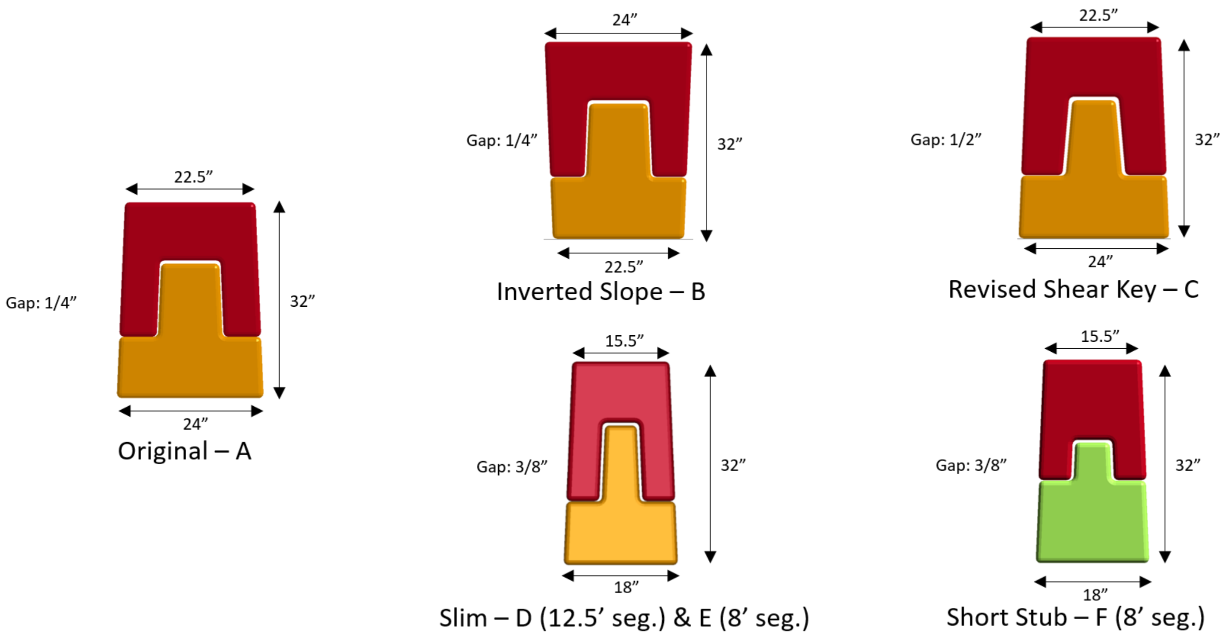


Figure 185. Variations of Concept No. 19

Table 73. Variations of Concept No. 19

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 74. All of the concept no. 19 variations produced very low barrier deflections combined with improved vehicle stability as compared to the current F-shape portable barrier. Concept nos. 19A, 19B, and 19C experienced smaller deflections than the other concept no. 19 variations due to their larger relative barrier mass. However, concept no. 19C experienced more deflection than concept nos. 19A and 19B due to the larger gap in between the interlocking stub and upper barrier section sidewalls. Concept no. 19C would also provide for more allowable horizontal curvature in a given barrier installation. As such, further development of concept no. 19 may need to consider the potential trade off between limited deflection and installation curvature needs. Inverting the barrier slope in concept no. 19B did provide slight reduction in bumper climb and roll, but the effect was minimal.

Table 74. 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

Concept nos. 19D and 19E were lighter than the first three variations due to their reduced width, but experienced higher displacements the previous variations based on a combination of decreased mass, increased gap tolerance, and/or shorter segment length. However, the displacements were still well below the design goal of 36 in. Barrier segment widths of only 18 in. may be hard to reinforce with standard rebar bend radii, and the narrow stub and sidewall widths may be more susceptible to damage during impact. Thus, it was noted that an intermediate section size with a width of 21 in. may provide the best combination of constructability, mass, barrier footprint, durability, and dynamic deflection. Segment length could still be varied to improve curvature.

Excessive tipping behavior was observed in the simulation for concept no. 19F, and it was determined that the shortened stub was allowing barrier segments to rotate and lift up adjacent barrier 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 186. To avoid this tipping behavior, modification to the size and shape of the interlocking stub would be needed and could be conducted under future phases of the research. However, the general design of concept no. 19 was acceptable and resulted in displacements that were 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 displacements and overall barrier performance that were observed.

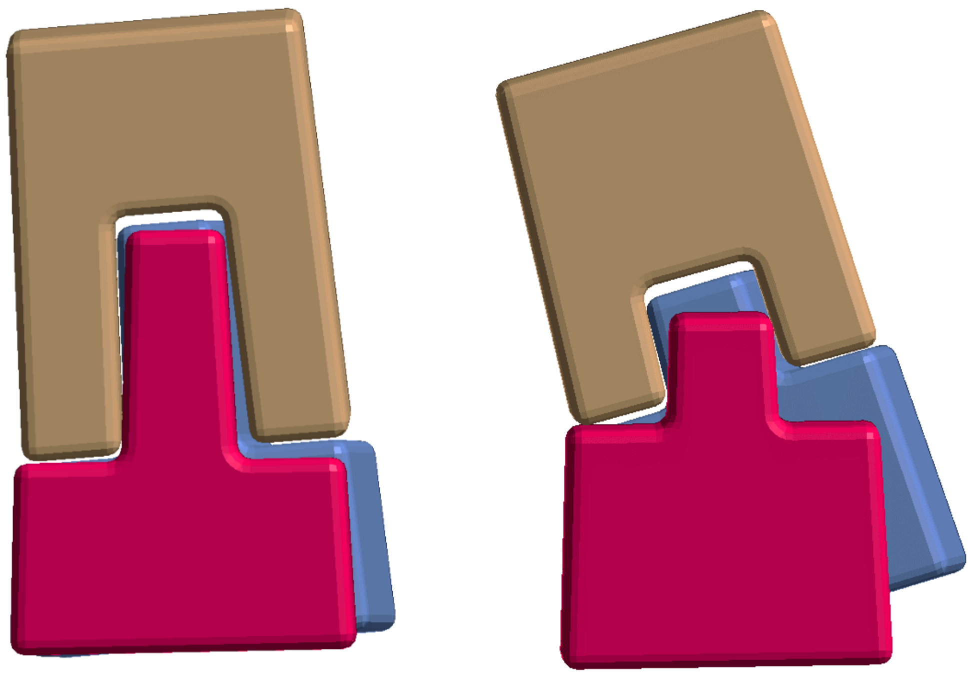


Figure 186. Comparison of Tipping Behavior in Concept nos. 19E (left) and 19F (right)

8.7 Simulation of Concept No. 16

The first variation simulated of concept no. 16 consisted of identical, rectangular concrete sections stacked on top of one another and offset by one half of the segment length. The stacked sections were connected by a series of four drop pins and measured 18 in. wide by 32 in. tall and weight approximately 580 lb/ft. These details are listed in Table 75. The results for the first variation of the concept, concept no. 16A are provided in Table 76, with sequential views of the simulation shown in Figure 187.

Table 75. 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 76. 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

Figure 187. Sequential Views of Concept No. 16A Simulation

Barrier tipping was observed in the simulation of concept no. 16A which can be seen in the sequential images above. While this behavior did not result in a reduction in vehicle stability, it was deemed undesirable to have tipping and uplift of the barrier segments. Two variations of concept no. 16 were simulated to try 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. Narrowing of the section width was desired to reduce the barrier weight per foot, and the pin diameter was increased to reduce of bending in the drop pins which was observed to contribute to separation between the top and bottom barrier segments and induce tipping in the simulation of concept no. 16 A. Tipping of the barrier segments was still observed in the simulation for concept no. 16B. Thus, concept no. 16C featured an 18-in. width and the larger, 1.75-in. diameter drop pins. Tipping behavior was still observed in the simulation for concept no. 16C, but it was reduced from the amount seen with concept nos. 16A and 16B. The barrier measurements for the three variations of concept no. 16 are listed in Table 77, and the simulation results are compared in Table 78.

Table 77. 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 78. 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 of the variations meet the displacement goals and do 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 concept design.

8.8 Discussion and Comparison of Simulation Results

Once all of the simulations were completed and the results were analyzed individually, bar plots were created to easily compare each of the design concepts and their variations as well as the original F-shape PCB design. These plots were analyzed by MwRSF team members and later presented during a meeting to sponsors to illustrate the differences between the design concepts. Figure 188 shows a comparison of the cross-sections of all of the design concepts, so that they are easily identifiable in the following bar plots.

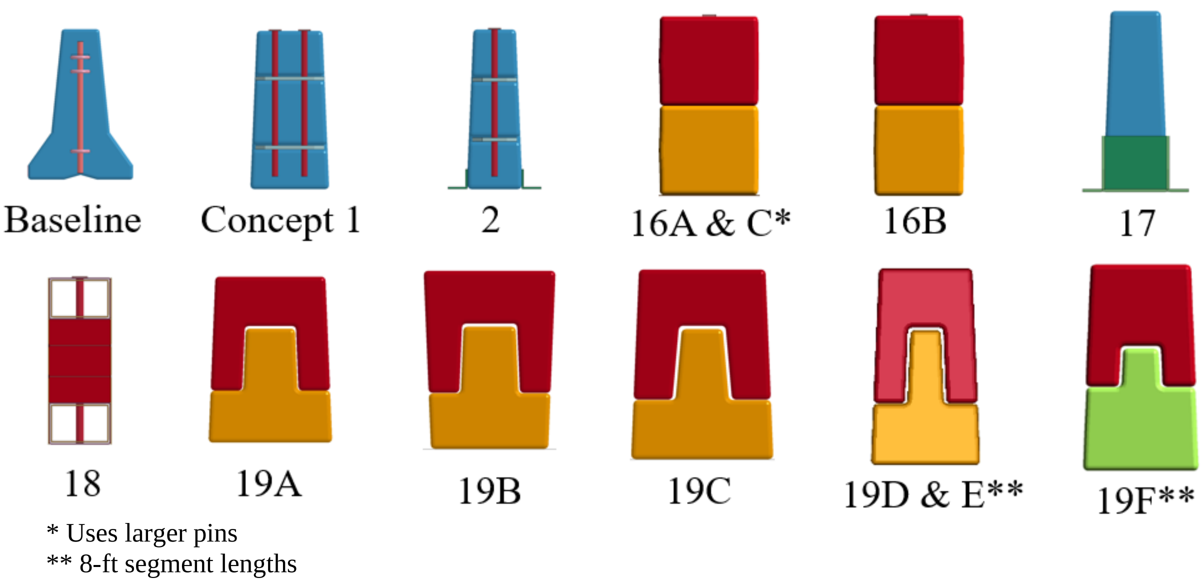


Figure 188. Visual Comparison of Design Concept Cross-Sections

Researchers first compared the impact performance of the proposed design concepts based on the simulation results. Barriers were compared in terms of maximum dynamic lateral barrier deflection, vehicle stability as evidenced by vehicle bumper climb and pitch and roll angles, and occupant risk criterion. Figure 189 through Figure 196 compare these values for all of the simulated concepts. Review of these parameters found that all of the proposed barrier designs had lateral barrier deflections below that of the current F-shape PCB. However, concept nos. 2, 17, and 18 did not provide barrier deflections below the 36 in. design criteria. These concepts failed to meet the deflection target due to a combination of their connection design and lower mass per foot of barrier length. The use of a vertical or near-vertical shape for the barrier concepts provided much improved vehicle stability. Vehicle roll varied slightly between the simulated concepts and the original F-shape barrier, but all roll values represented good vehicle roll behavior. More promising were large reductions in vehicle pitch and bumper climb values for the simulated concepts as compared to current F-shape PCB. This indicated improved stability for the proposed designs. Review of the occupant risk criteria for all of the simulated concepts found a general reduction in the longitudinal Occupant Impact Velocity (OIV) and Occupant Ridedown Acceleration (ORA) as compared to the current F-shape PCB, but slight increases in the lateral OIV and ORA values. All occupant risk values were within the MASH limits. The observed effect on occupant risk values was not unexpected due to the use of a vertical or near-vertical barrier geometry. Overall, the impact performance of the simulated concepts indicated that the proposed concepts provided significant reduction in barrier deflection with increased vehicle stability while not adversely affecting occupant risk. The most desirable barrier performance was observed for concept nos. 1, 16, and 19 as these concepts provided the greatest reduction in barrier deflection while still providing increased stability and acceptable occupant risk values.

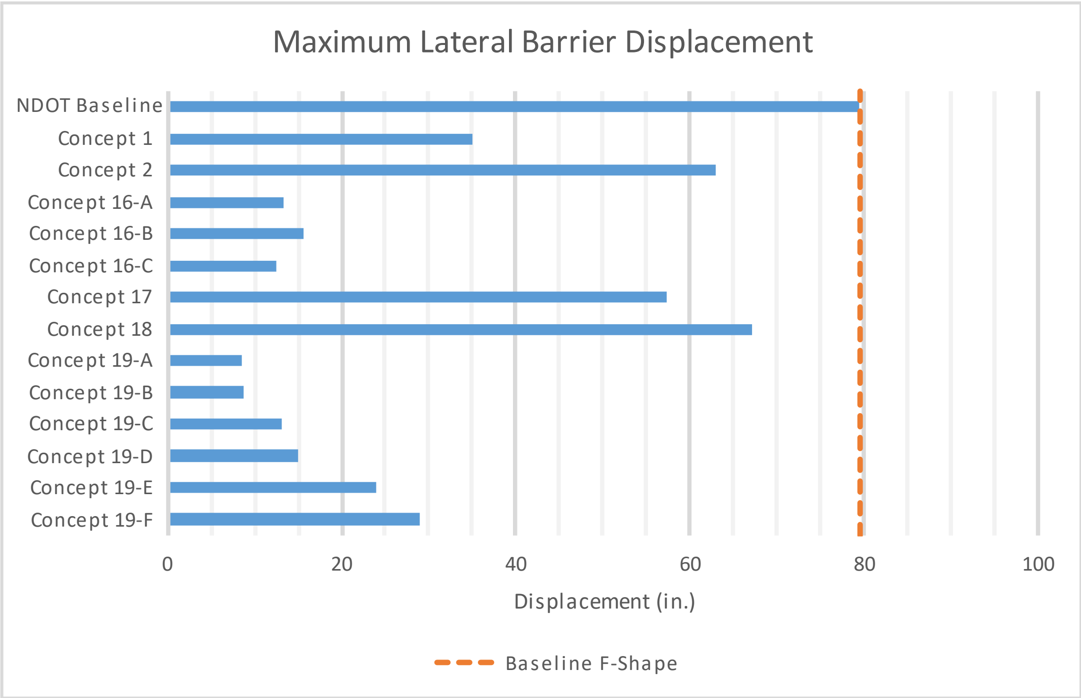


Figure 189. Comparison of Simulated Barrier Concepts Lateral Displacements

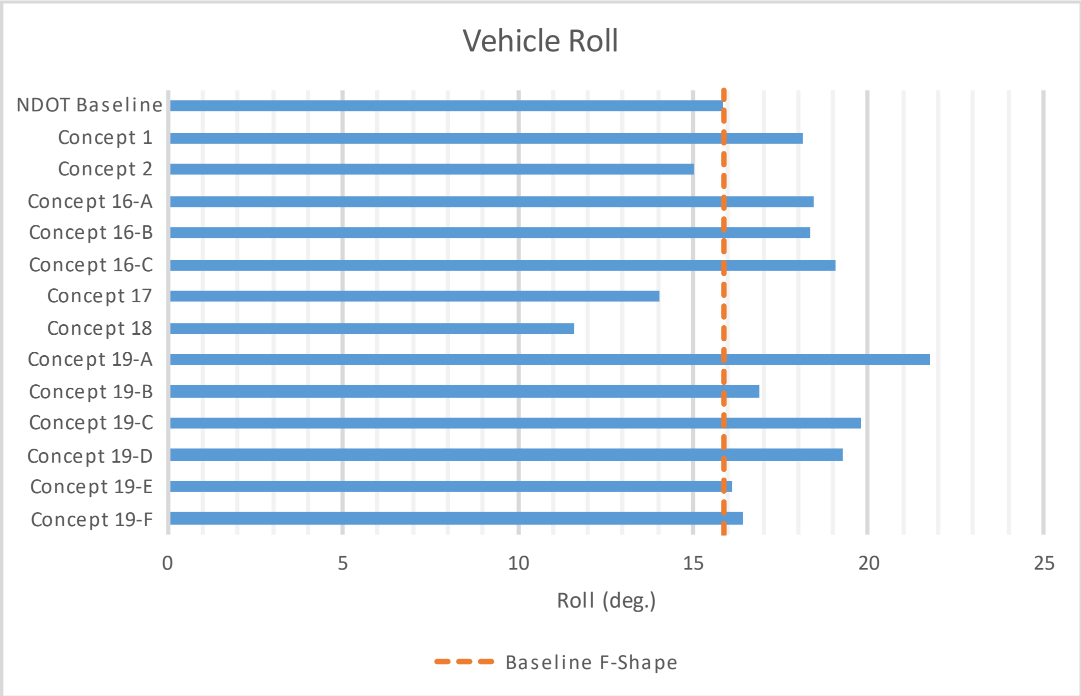


Figure 190. Comparison of Simulated Barrier Concepts Lateral Roll Angle

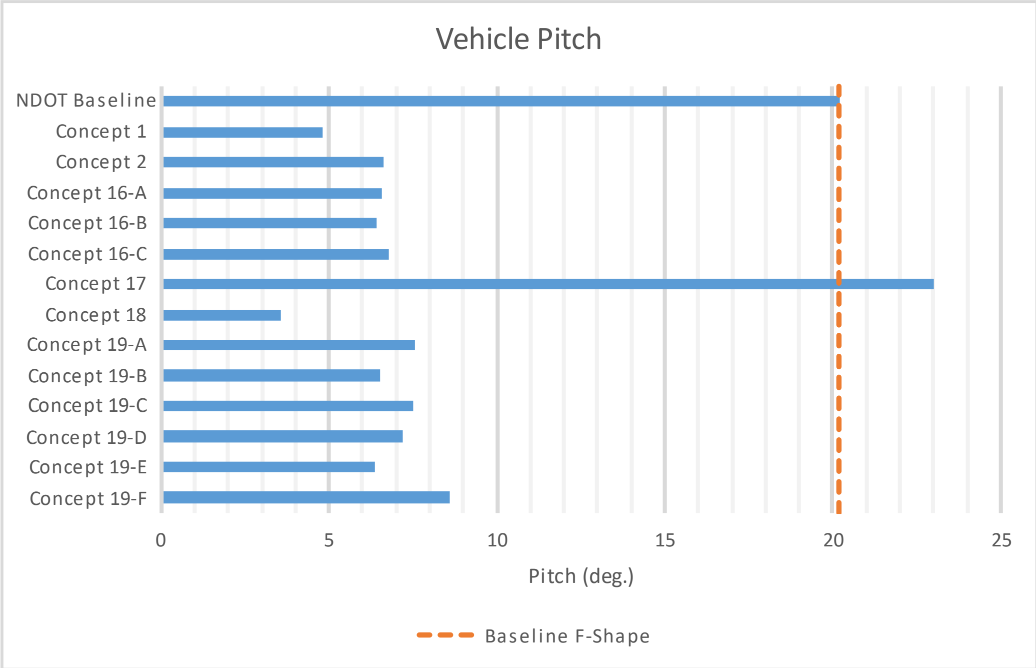


Figure 191. Comparison of Simulated Barrier Concepts Lateral Pitch Angle

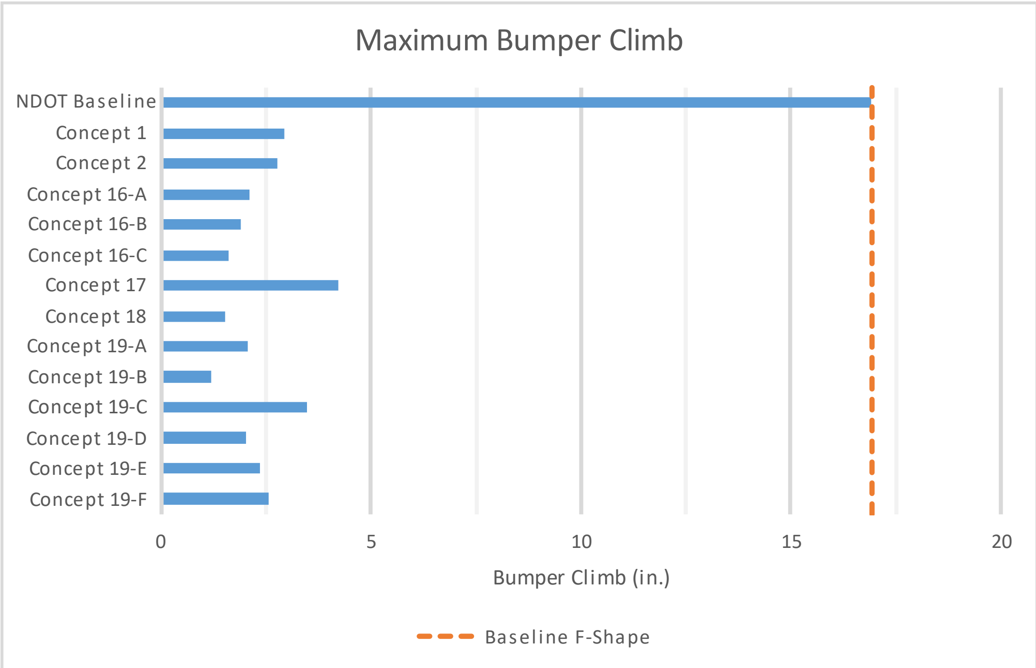


Figure 192. Comparison of Simulated Barrier Concepts Bumper Climb

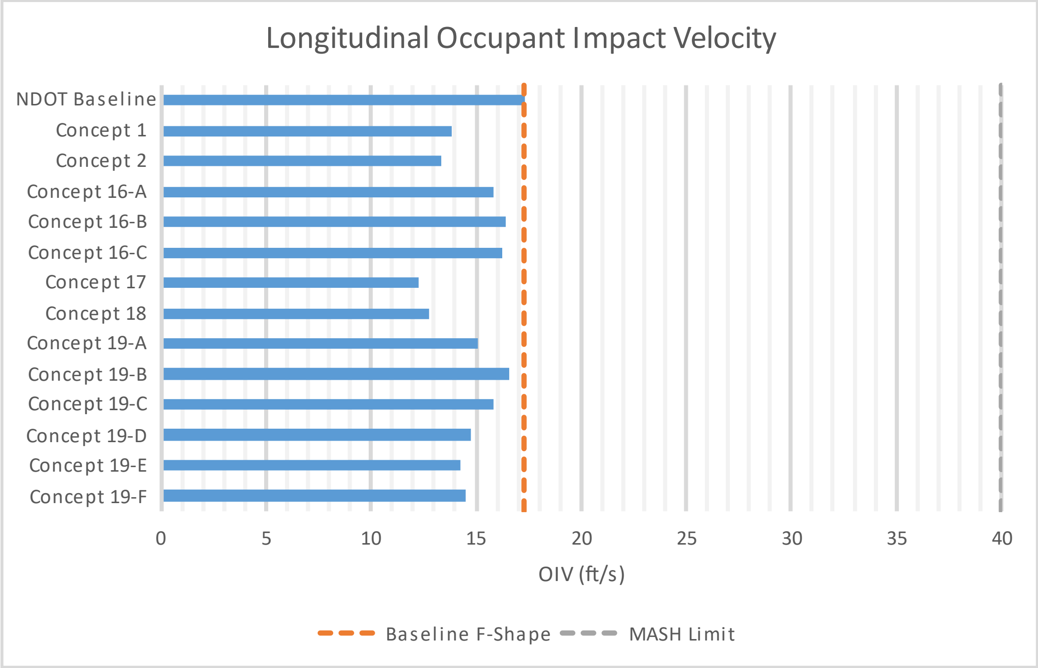


Figure 193. Comparison of Simulated Barrier Concepts Longitudinal OIV

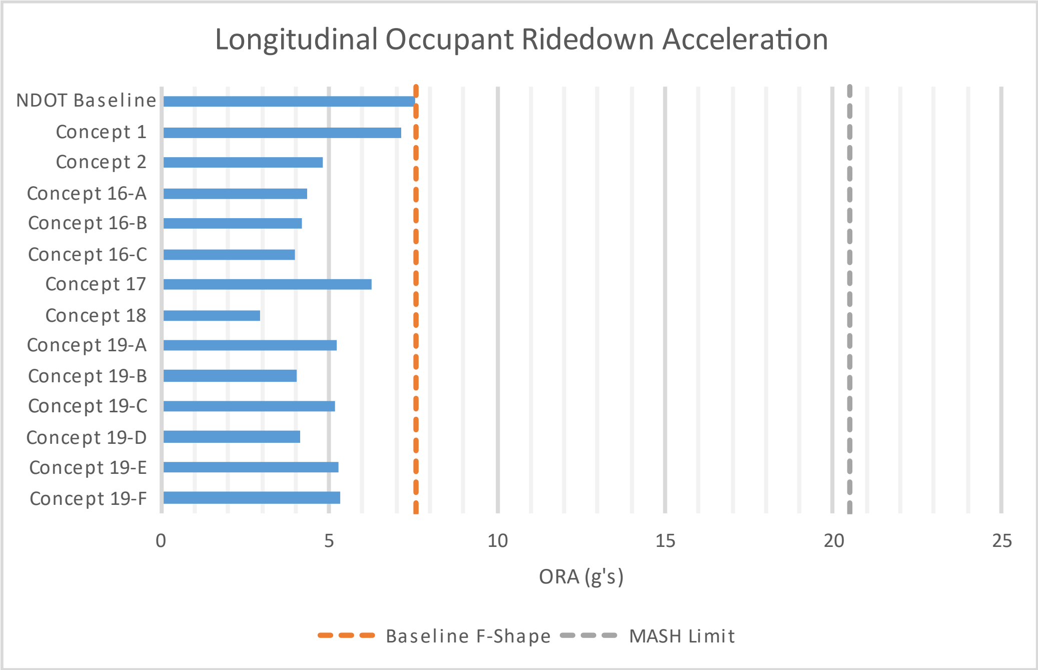


Figure 194. Comparison of Simulated Barrier Concepts Longitudinal ORA

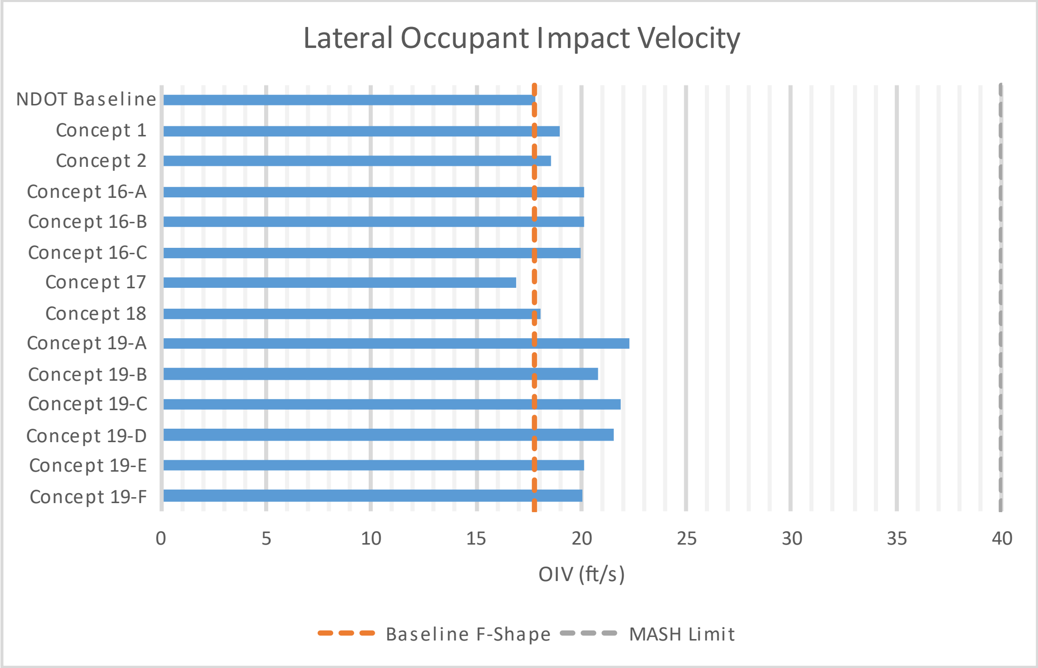


Figure 195. Comparison of Simulated Barrier Concepts Lateral OIV

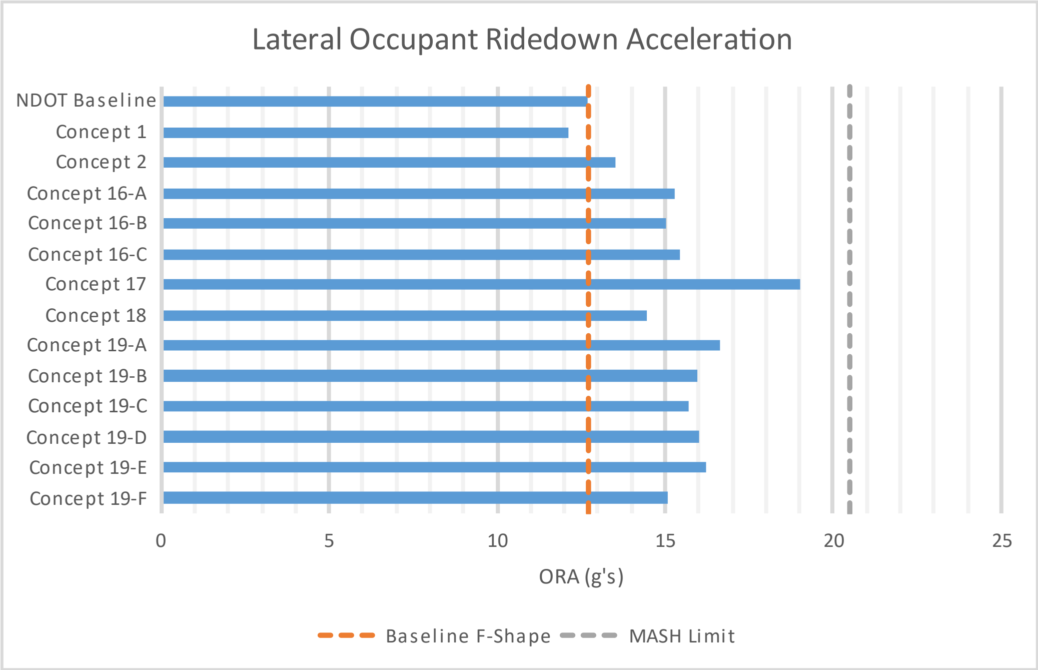


Figure 196. Comparison of Simulated Barrier Concepts Lateral ORA

Because the mass or weight of the barrier segments was an important consideration for end users, further comparisons were made with respect to the individual barrier section lengths and the weight per foot of the various concepts. As noted previously, design criteria for the new barrier concepts limited the mass of any barrier segment to less than 7,000 lbs for lifting equipment considerations. All the proposed barrier concepts had segment weights under the proposed limit, as shown in Figure 197. In fact, all of the concepts other than concept no. 1 had segment weights less than the current F-shape PCB. Of course, some of those segment weights were reduced due to the use of stacked barrier segments to form the barrier system in concept nos. 16 and 19. As such, comparison of the barrier concepts was shown based on a weight per linear foot basis in Figure 198.

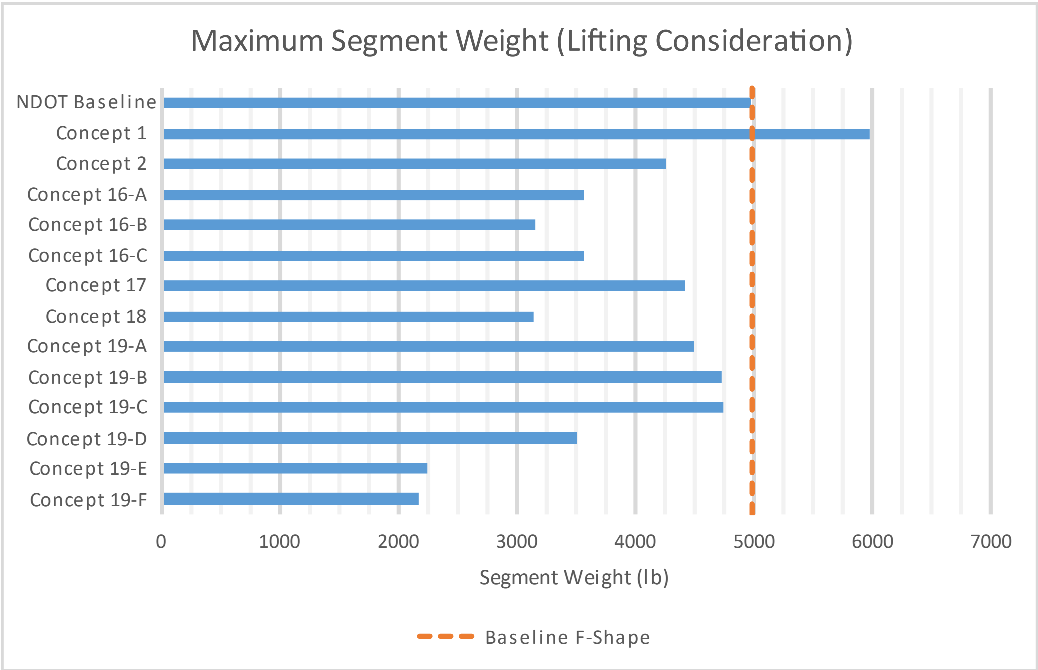


Figure 197. Comparison of Simulated Barrier Concepts Segment Weight

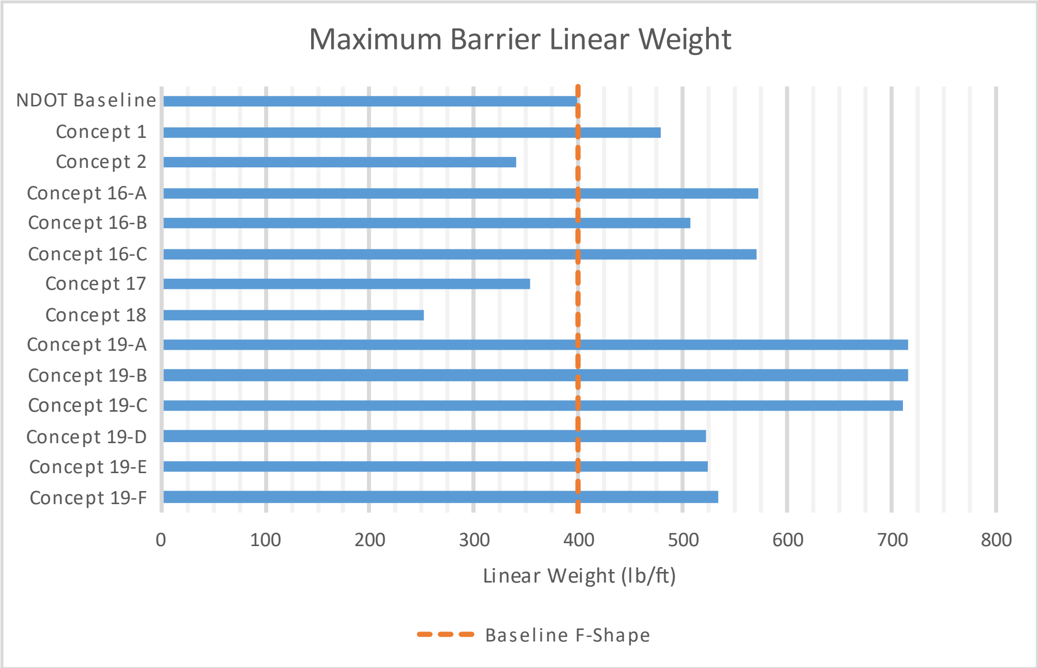


Figure 198. Comparison of Simulated Barrier Concepts Weight per Linear Foot

While several of the concepts have significantly more weight per foot that the current F-shape PCB, the results of the simulation analysis suggested that increased barrier weight or mass was a major factor in the effectiveness of the concepts in reducing barrier deflection. Figure 199 shows the relationship between the weight per linear foot and the lateral barrier deflection of each of the simulated barrier designs. A clear trend was observed demonstrating that increased barrier weight reduced barrier deflections. This trend is due to the increased barrier weight providing additional inertial resistance as well as increased friction forces between the barriers and the road surface. As such, increased barrier weight may be beneficial to barrier performance. Of course, barrier weight increases will need to be balanced with operational concerns such as lifting and installation as well as dead loads on bridge decks. This will be further investigated in future phases of the research.

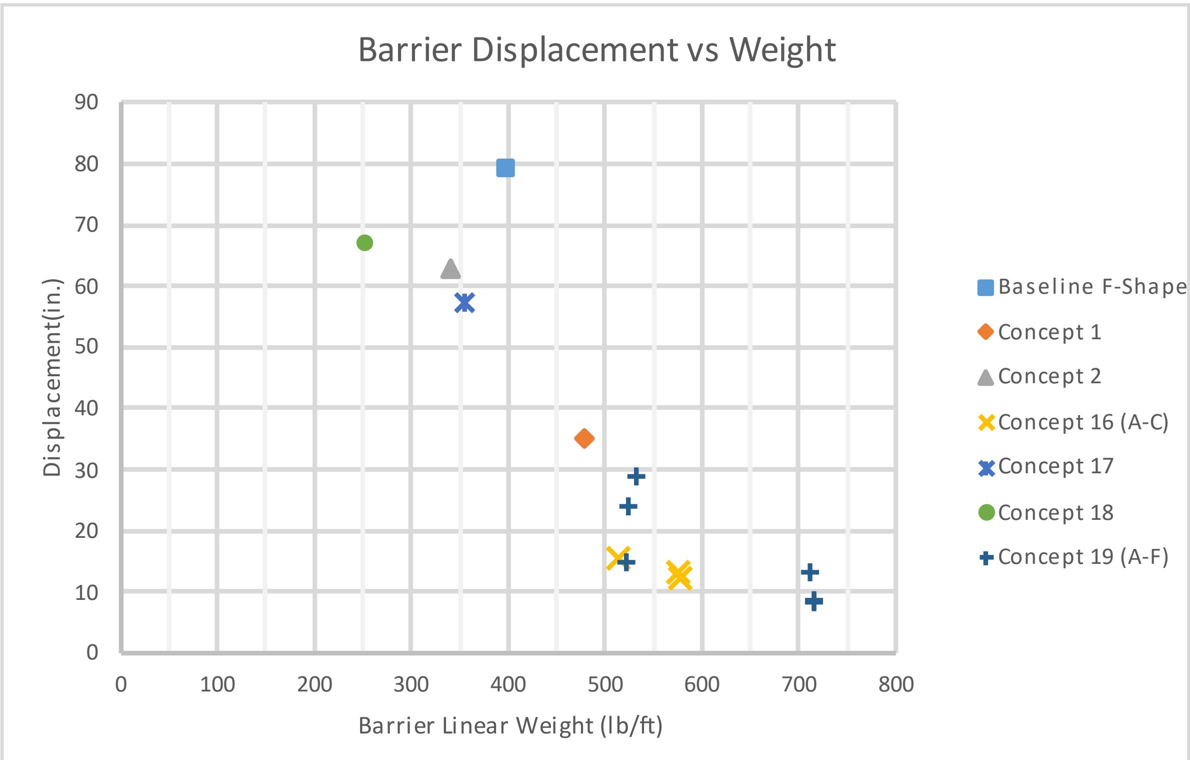


Figure 199. Simulated Barrier Concepts Lateral Deflection Versus Weight per Linear Foot

Figure 199 also demonstrated the importance of a more effective joint connection with moment continuity. The current F-shape PCB design displayed significantly higher deflections than all of the proposed concepts. This included concepts with less weight per linear foot. This suggested that the pin and loop connection used in the F-shape PCB provided more relative barrier rotation prior to loading adjacent barrier segments and less effective load transfer which led to higher barrier deflections. Thus, barrier weight or mass and connection design both appear to be instrumental in reducing barrier deflections.

A subsequent research effort to identify and further develop a preferred concept for full-scale crash testing has been funded by the Midwest Pooled Fund Program. Data from this report and the simulation comparisons detailed herein will be used to help identify preferred concepts for further development.

9 SUMMARY AND CONCLUSIONS

The objective of this research project was to develop a non-proprietary, high-performance portable barrier capable of meeting the MASH TL-3 safety requirements with reduced free-standing barrier deflections and increased vehicle stability as compared to existing, widely used PCB systems.

Initially, a literature review was conducted to gather information about portable barrier systems currently in use. A study performed by TTI surveyed DOTs and found that most states utilized F-shape or New Jersey shaped concrete barriers with the pin and loop connection. This configuration resulted in high deflections and the barrier shape induces vehicle climb when impacted. Existing portable barrier designs were reviewed including barrier shape, material, and connection design. Full-scale crash testing performed on portable barriers according to NCHRP Report 230, NCHRP Report 350, MASH, and EN 1317-2 evaluation criteria was also collected and reviewed. The following information from each test was collected and utilized for concept design purposes: material, connection, shape, anchorage, retrofit, pass/fail, impact severity, deflection, barrier height to weight ratio, and segment length.

Alternate concretes were researched in hopes of increasing portable barrier service life. Installers noted current portable barriers crack and spall during transportation and installation, especially at the toes because they are unreinforced, and some existing barriers can sustain heavy damage during impact. UHPC, FRC, and polymer concretes were reviewed for their potential use in a new portable barrier design. UHPC was not recommended for the new portable barrier due to cost and fabrication difficulty. Polymer concrete may require special mixing equipment and was noted to be too expensive for large projects, making it an unlikely choice for the new portable barrier. It was noted that adequate barrier strength is unlikely to be achieved without traditional steel reinforcement, but alternate concretes could be used to limit cracking, spalling, or other damage seen on the barrier due to transportation, installation, and impact. It was recommended to focus design of the new portable barrier system on traditional concrete mixes for minimizing initial costs and ease of implementation, and alternative concretes could be investigated once a barrier has been developed and put into service.

A survey was sent to state DOTs, concrete barrier fabricators, installers, and consultants for prioritizing new portable barrier design criteria. Cost was ranked as high importance, with respondents willing to accommodate a cost of approximately $100 per foot of barrier. The preferred material for the new portable barrier was concrete, but steel would be acceptable if cost was not prohibitive. Ease of transportation, installation, connection installation, and inspection were ranked highly by most respondents. A maximum barrier weight of 7,000 lb and length between 10 and 14 ft were preferred by many respondents. Majority of respondents requested a 32-in. tall barrier for consistency and easy transition to current roadside barrier installations. Furthermore, it should be noted that transition barrier sections between the new portable barrier and other roadside barrier installations may need to be designed and tested. Drainage and curvature accommodation were noted as important for barrier functionality, but further research was needed to better define those parameters. Finally, many respondents requested a free-standing dynamic deflection of less than 3 ft for the new portable barrier for MASH test designation no. 3-11.

Following the survey and review of existing literature, basic design criteria for the new portable barrier system were established.

- Cost less than $100 per linear foot

- Materials would focus on conventional concrete mixes with the potential to investigate alternative concrete materials in the future. Steel would be considered as well.

- It was desired to improve durability of the new barrier design as compared to existing barriers if it could be done within cost targets

- Design concepts should consider ease of transportability and lifting and limit barrier segment weights to less than 7,000 lbs.

- The barrier geometry would focus on a vertical or near vertical shape for stability. Barrier height would be targeted at 32 in., length would be targeted at 12.5 ft, and the barrier footprint would be 24 in. or less.

- Barrier installation would focus on ease of barrier placement and simple connections that did not require tools. Ease of inspection of installed barriers would also be important.

- Curvature and drainage would be important barrier parameters.

- Barrier anchorage and transition to other barrier systems would not be directly developed initially, but would be considered during the design.

- Barrier deflections should be limited to less than 3 ft.

- Vehicle stability should be improved over current safety shape PCB systems.

- The barrier system should mee MASH TL-3 safety criteria.

A series of design concepts were developed to address these criteria. The majority of the concepts were precast concrete designs, but one steel design was considered. These design concepts were presented to WisDOT and five were selected for additional evaluation and development.

The Mid-American Transportation Center (MATC) funded a parallel research project titled *Development of a New Generation of Portable Concrete Barriers* which simulated these selected design concepts under MASH test designation no. 3-11 impact conditions using LS-DYNA. Variations of the five concepts preferred by WisDOT and one additional concept were simulated using LS-DYNA to evaluate their performance. Simulation of the concepts found that barrier weight or mass and connection design both appeared to be instrumental in reducing barrier deflections, and that the use of vertical or near vertical shapes improved vehicle stability. Results from the simulation analysis identified three preferred concepts that met the design criteria. The three preferred concepts were:

1. Concept no. 1 – A near-vertical face PCB with a steel plate and drop pin connection

2. Concept no. 16 – A near-vertical face PCB comprised of stacked and offset rectangular segments connected with steel drop pins.

3. Concept no. 19 – A near-vertical face PCB comprised of interlocking top and bottom segments that are stacked in an offset or staggered configuration to provide continuity in the barrier without discrete barrier connections or connection hardware between the barrier segments

Data from this research effort will be used to help identify preferred concepts for further development of the new portable barrier design. The Midwest Pooled Fund program has currently funded follow-on research to further develop preferred design concepts into a prototype design for full-scale crash testing and full-scale crash testing of the prototype to MASH TL-3. These research efforts will develop the detailed design of a preferred concept, including determination of final barrier geometry considering mass, curvature, and other considerations, design of barrier structural reinforcement, drainage accommodations, and lifting accommodations.

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11 APPENDICES

Appendix A. Portable Barrier Design Criteria Survey

Midwest Roadside Safety Facility
University of Nebraska

WisDOT TL-3 Portable Barrier Design Criteria Survey

Figure A-1. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 1

The Midwest Roadside Safety Facility (MwRSF) is currently working on a research effort with the Wisconsin Department of Transportation (WisDOT) to develop a new, MASH TL-3 portable barrier system. The objective of this research project is to develop a non-proprietary portable barrier capable of meeting the MASH TL-3 safety requirements and with reduced free-standing barrier deflections and increased vehicle stability as compared to existing, widely-used portable concrete barrier (PCB) systems. This portable barrier could be widely implemented in most applications, and future research could be conducted to further reduce deflections from the baseline design. The potential for future anchoring of the barrier to further limit deflections would be considered during the high-performance portable barrier development. Note that the barrier could be an original design or a modified version of the other systems. Also note that the barrier system is not limited to any certain material or shape. The recommended barrier system should have a practical length and weight such that typical construction equipment can be used for placement, repositioning, etc.

As part of that effort, a series of design criteria were developed to help guide and focus the development of the new barrier system. However, ranking and defining the design criteria by the end users of the barrier system is vital to developing a barrier system that best meets the needs of end users, including state DOTs, fabricators and contractors/installers. To that end MwRSF has prepared a survey of the proposed design criteria to help rank their importance. Please rank or denote your preference regarding the design criteria below.

Participant Information *

Name

State DOT

Business Affiliation

Respondent is a: *

- State DOT
- Barrier Fabricator
- Barrier Installer
- Consultant
- Other

Since you are part of a State DOT, please denote the area in which you reside. (i.e. traffic, roadway design, structures, etc.)

Figure A-2. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 2

Portable Barrier Cost - The current F-shape PCB can be obtained for $600 - $1,000 per 12.5-ft long barrier segment.

1. Please rank the cost of the new portable barrier as high, medium, or low importance.
   - High
   - Medium
   - Low

2. Would you be willing to accommodate higher costs if durability and life cycle of the barrier was increased?
   - Yes
   - No

3. Given the current F-shape PCB system costs ($48 - $80 per linear ft) and an estimated service life for that barrier segment of 5-10 years, what level of initial barrier cost per linear foot would be acceptable to increase the barrier service life over 20 years?

   ______ dollars/linear foot

4. Given the current F-shape PCB system costs ($48 - $80 per linear ft) and that the barrier system sustains significant damage and must be replaced following a TL-3 impact, what level of initial barrier cost per linear foot would be acceptable to reduce the damage during TL-3 impact such that the barrier segment could be reused?

   ______ dollars/linear foot

Materials – Current portable barrier systems are primarily comprised of reinforced concrete. Reinforced concrete is simple and low-cost to fabricate and has high mass and inertial resistance. However, steel and plastic portable barrier systems have been developed and met safety criteria. Steel portable barriers allow for more flexibility in overall design and allow for more robust and innovative connection designs, but are generally more expensive in terms of initial cost, may cost more to replace if damaged, and their lower mass per unit length lowers their inertial resistance and increases free-standing barrier deflections. Plastic portable barriers are generally low cost, but they require additional structural reinforcement and have the highest free-standing barrier deflections due to their low mass and inertial resistance.

5. Material Preference – Please rank your preferred portable barrier material from 1 to 3 (1 being the highest).

	1	2	3
Reinforced Concrete	○	○	○
Steel	○	○	○
Plastic	○	○	○

Figure A-3. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 3

6. Alternative Concretes – Currently several alternative concrete mixtures are available that incorporate polymers or various types of distributed fibers to improve the strength and performance of the concrete, increase its toughness, and reduce damage. Would the use of alternative concrete mixtures be something that should be considered in a new portable barrier design?

- Yes
- No

7. Ballast – Would the use of ballast to increase the mass and inertial resistance of steel and/or plastic portable barriers be something that should be considered in a new portable barrier design?

- Yes
- No

8. A steel portable barrier design could focus on increased durability, reusability, and extended life cycle for an increased initial barrier cost. Alternatively, a steel portable barrier design could focus on a lower initial cost with reduced durability and shorter life cycle. What type of steel portable barrier design is preferred?

- Higher initial cost and increased durability
- Lower initial cost and reduced durability

Durability – The current F-shape PCB is can be damaged during regular operations, transport, and installation. The current F-shape PCB also can be significantly damaged during vehicle impacts. Damage to the barrier from either source can reduce the service life of the barrier.

9. Please rank the durability of the new portable barrier during work zone operations as high, medium, or low importance.

- High
- Medium
- Low

10. Please rank the durability of the new portable barrier during transport as high, medium, or low importance.

- High
- Medium
- Low

11. Please rank the durability of the new portable barrier during installation as high, medium, or low importance.

- High
- Medium
- Low

Figure A-4. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 4

Installation/Operational Concerns – Please rank or mark the appropriate responses below.

12. Please rank the importance of ease of transportability of the new portable barrier design. This would include ease of shipping, ease of lifting and positioning, and lifting attachments.

- High
- Medium
- Low

13. Barrier Mass - Please indicate a maximum allowable weight for the new portable barrier design based on available installation equipment and other concerns.

- < 5,000 lbs
- 5,000 lbs - 6,000 lbs
- 6,000 lbs - 7,000 lbs
- 7,000 lbs - 8,000 lbs
- 8,000 lbs - 9,000 lbs
- 9,000 lbs - 10,000 lbs
- > 10,000 lbs

14. Barrier Length – Please indicate your preferred portable barrier segment length.

- < 10 ft
- 10 ft - 12 ft
- 12 ft - 14 ft
- 14 ft - 16 ft
- 16 ft - 18 ft
- 18 ft - 20 ft
- > 20 ft

Portable barrier installation includes considerations of several factors that affect barrier installation. Please rank the following installation factors in terms of their importance as high, medium, or low.

15. Barrier Placement – the ability to place and install the barrier either horizontally or vertically without interference from adjacent barrier segments.

- High
- Medium
- Low

Figure A-5. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 5

16. Segment Connections – the ease of the barrier-to-barrier segment connections in terms of ease of installation and eliminating the need for tools to install segment connections.

- High
- Medium
- Low

17. Curvature and Tolerances – the ability to install the barrier system on horizontal and vertical curves as well ad deal with vertical variations in the roadway surface.

- High
- Medium
- Low

18. Drainage – the ability for water flow to occur through slots in the base of the barrier segment.

- High
- Medium
- Low

19. Ease of Inspection – the ease with which the barrier can be reviewed for ensuring proper installation.

- High
- Medium
- Low

20. If your current barrier systems have drainage slots, what length of drainage slot do you currently require/desire per linear foot of barrier?

[ ] ft drainage slot/ft barrier

21. What minimum radius of horizontal curvature do you require for your portable barrier installations?

[ ] ft

22. What maximum flare rate do you install portable barriers at in the field?

[ ]

Figure A-6. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 6

23. What is the maximum vertical curvature or percent grade you would require for portable barrier installations? (Click box and enter value)

- [ ] Maximum Vertical Curvature (ft)
- [ ] Percent Grade (%)

Safety Performance - Please rank or mark the appropriate responses below.

24. Ability of the barrier to withstand MASH TL-3 impact loads with limited, to minimal damage.

- High
- Medium
- Low

25. Use of vertical or near-vertical barrier shape to reduce vehicle climb and roll and improve vehicle stability.

- High
- Medium
- Low

26. Barrier Height – The current F-shape PCB is 32-in. tall. However, there is potential for a new MASH TL-3 portable barrier be shorter than 32 in. However, shorter barriers may complicate future transitions to existing barrier systems such as guardrail and concrete parapets that are 31 in. to 32 in. tall. Please indicate the desired height for the new portable barrier system.

- 32 in.
- > 32 in.

27. Is there a desire to develop the portable barrier system to meet TL-4 with the requirements that the barrier height and reinforcement would need to increase?

- Yes
- No

Figure A-7. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 7

28. Dynamic Deflections for Free-Standing Barrier– Please indicate your preferred portable barrier segment free-standing deflection under MASH TL-3 impact conditions.

- < 2 ft
- 2 ft - 3 ft
- 3 ft - 4 ft
- 4 ft - 5 ft
- 5 ft - 6 ft
- 6 ft - 7 ft
- > 7 ft

29. End users often desire anchorage systems for portable barriers used in deflection restricted applications. Please mark desired road surface(s) for anchorage.

- Asphalt
- Concrete
- Concrete with asphalt overlay
- Graded shoulder or gravel
- Other (please specify)

30. Transitions – While barrier transitions cannot be designed within the scope of this initial effort, it would be worthwhile to identify what barrier systems end users anticipate attaching to the new portable barrier system. Please mark any barrier systems that you would consider for attachment to a new portable barrier system.

- F-Shape permanent concrete barrier or bridge rail
- New Jersey shape permanent concrete barrier or bridge rail
- Single slope permanent concrete barrier or bridge rail
- Vertical shape permanent concrete barrier or bridge rail
- Steel bridge rail
- W-beam guardrail/MGS
- Thrie beam guardrail
- Anchored portable barriers
- Crash Cushions
- Other (please specify)

Figure A-8. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 8

31. In the space below, please note any other design considerations that you believe are important for the new, MASH TL-3 portable barrier design as well as any additional comments you may have.

Thank You!

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

Figure A-9. WisDOT TL-3 Portable Barrier Design Criteria Survey – Page 9

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