Midwest Pooled Fund Research Program
Fiscal Year 2019 (Year 29)
Research Project Number TPF-5(193) Supplement #139

EVALUATION OF PERMANENT CONCRETE BARRIERS TO MASH 2016

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Nebraska Department of Transportation
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MwRSF Research Report No. TRP-03-454-24

August 14, 2024

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TRP-03-454-24		

4. Title and Subtitle Evaluation of Permanent Concrete Barriers to MASH 2016	**5. Report Date** August 14, 2024 **6. Performing Organization Code**
7. Author(s) Hovde, S.E., Steelman, J.S., Rosenbaugh, S.K., Faller, R.K., Revell, J.R., and Bielenberg, R.W.	**8. Performing Organization Report No.** TRP-03-454-24
9. Performing Organization Name and Address Midwest Roadside Safety Facility (MwRSF) Nebraska Transportation Center University of Nebraska-Lincoln Main Office: Prem S. Paul Research Center at Whittier School Room 130, 2200 Vine Street Lincoln, Nebraska 68583-0853 Outdoor Test Site: 4630 N.W. 36th Street Lincoln, Nebraska 68524	**10. Work Unit No.** **11. Contract** TPF-5(193) Supplement #139
12. Sponsoring Agency Name and Address Midwest Pooled Fund Program Nebraska Department of Transportation 1500 Nebraska Highway 2 Lincoln, Nebraska 68502	**13. Type of Report and Period Covered** Final Report: 2019 - 2024 **14. Sponsoring Agency Code** RPFP-19-CONC-1

15. Supplementary Notes

Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The objective of this research project was to develop criteria and methodology to evaluate permanent concrete barriers to MASH 2016 TL-3 and TL-4 without crash testing, and then use that methodology to evaluate the crashworthiness of permanent concrete barrier standard plans provided by the sponsoring agencies of the Midwest Pooled Fund Program. A literature review was conducted to determine evaluation criteria for stability, shape, strength, and anchorage, and a database of permanent concrete barrier crash tests was compiled. The members of the Midwest Pooled Fund Program were surveyed to collect barrier standard plans, and a subset of these barriers were selected for evaluation. A total of 85 permanent concrete barrier configurations were evaluated. In total, 22 barrier configurations were evaluated as crashworthy to MASH TL-4 and an additional 42 configurations were deemed crashworthy to MASH TL-3. Bending and shear capacities were calculated and compared to the design loads for each Test Level. Significant strength overdesign was commonly observed throughout the details provided by the sponsoring agencies, suggesting that agencies could potentially reduce costs for many of their barrier configurations by optimizing reinforcement patterns. Some of the barrier evaluations were inconclusive because no computational method or suitable comparative crash tests were available to justify barrier performance, and this provided insight into potential future research opportunities.

17. Key Words	18. Distribution Statement
Highway Safety, Roadside Appurtenances, MASH 2016, Permanent Concrete Barrier	No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	255	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER STATEMENT

ACKNOWLEDGEMENTS

The authors wish to acknowledge several sources that made a contribution to this project: (1) the Midwest Pooled Fund Program funded by the California Department of Transportation, Florida Department of Transportation, Georgia Department of Transportation, Hawaii Department of Transportation, Illinois Department of Transportation, Indiana Department of Transportation, Iowa Department of Transportation, Kansas Department of Transportation, Kentucky Department of Transportation, Minnesota Department of Transportation, Missouri Department of Transportation, Nebraska Department of Transportation, New Jersey Department of Transportation, North Carolina Department of Transportation, Ohio Department of Transportation, South Carolina Department of Transportation, South Dakota Department of Transportation, Utah Department of Transportation, Virginia Department of Transportation, Wisconsin Department of Transportation, and Wyoming Department of Transportation for sponsoring this project; and (2) MwRSF personnel.

Acknowledgement is also given to the following individuals who contributed to the completion of this research project.

Midwest Roadside Safety Facility
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K.A. Lechtenberg, M.S.M.E., Research Engineer
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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 Background

National Cooperative Highway Research Program (NCHRP) Report 350, "Recommend Procedures for the Safety Performance Evaluation of Highway Features," was published in 1993 to guide testing and evaluation of roadside safety features [1]. However, due to continuously changing traffic conditions, an evolving vehicle fleet, and new knowledge gained through extensive research, sections of NCHRP Report 350 required updates. NCHRP Project 22-14(2), "Improvement of Procedures for the Safety-Performance Evaluation of Roadside Features" and NCHRP Report 665, "Identification of Vehicular Impact Conditions Associated with Serious Ran-off-Road Crashes," updated impact conditions and test vehicle specifications, and determined evaluation criteria to more accurately represent the current transportation climate [2]. In 2009, the American Association of State Highway and Transportation Officials (AASHTO) published the results of NCHRP Project 22-14(02) as the first edition of the Manual for Assessing Safety Hardware (MASH) [3]. The second edition of MASH was published in 2016 and implemented changes to several test vehicle dimensions, test documentation requirements, and developed a new matrix for the testing of cable barriers on slopes [4].

1.1.1 MASH Implementation

In December 2015, AASHTO and the Federal Highway Administration (FHWA) released a joint implementation agreement. The purpose of the agreement was to encourage state departments of transportation and hardware developers to advance their roadside safety device designs. The agreement established sunset dates for the evaluation of roadside safety features to MASH 2016 on the National Highway System (NHS). The sunset dates included in the agreement are presented in Table 1.

Table 1. MASH 2016 Implementation Sunset Dates

Sunset Date			Roadside Safety Features
Month	**Day**	**Year**	
Dec.	31	2017	W-beam barriers and cast-in place concrete barriers
Jun.	30	2018	W-beam terminals
Dec.	31	2018	Cable Barriers, cable barrier terminals, and crash cushions
Dec.	31	2019	Bridge rails, transitions, all other longitudinal barriers including portable barriers installed permanently, all other terminals, sign supports, and other breakaway hardware
Note: Temporary work zone devices, including portable barriers, manufactured after December 31, 2019, must have been successfully tested to the 2016 edition of MASH. Such devices manufactured on or before this date, and successfully teste to NCHRP Report 350 or MASH 2009, may continue to be used throughout their normal service lives.			

1.1.2 Federal-Aid Eligibility Letters

Traditionally, FHWA has reviewed details of new roadside safety hardware and delivered eligibility letters to those systems that were considered crashworthy to the applicable crash testing standards at the time. These letters provided state departments of transportation (DOTs) with the justification needed to receive federal reimbursement for safety hardware installed on NHS construction projects.

In a May 2017 open letter, FHWA established the following significant changes to the eligibility letter process: (1) for manufacturers and states to qualify for an FHWA federal-aid eligibility letter, all roadside hardware devices must complete the full suite of recommended tests as described in AASHTO MASH, and (2) FHWA will no longer provide federal-aid eligibility letters for modifications made to an AASHTO MASH-crash tested device [5]. The result of this letter was that systems that may be crashworthy to MASH 2016 would not be qualified to receive an eligibility letter without first being evaluated through expensive crash testing. Also, modifications made to systems currently holding an eligibility letter would not be awarded another letter without crash testing of the additional modifications.

However, in another open letter dated April 8, 2019, the FHWA clarified that design modifications may be considered for an eligibility letter if the modification occurs whilst the system is undergoing applicable crash testing, and the crash test laboratory documents the following in the test report accompanying the eligibility letter submission: (1) revision details to explain the type and extent of any revisions, (2) engineering rationale with adequate detail to explain the purpose of any revisions, and (3) engineering assessment of the expected performance on crash tests conducted on the device where design revisions were not present at the time of those tests [6].

FHWA has also stated that transportation agencies do not need an eligibility letter to obtain federal reimbursement. It will be up to agencies to work with their divisional FHWA offices to ensure that roadside hardware is crashworthy and, therefore, eligible for reimbursement. Thus, a review of the sponsoring agencies' permanent concrete barrier standard plans was necessary to determine barrier crashworthiness and provide the documentation and justification required to obtain federal reimbursement through the FHWA divisional offices.

1.2 Objective

The objective of the research effort was to perform a literature review and compile a crash testing database of currently crash tested permanent concrete barrier systems. The information gathered was used to synthesize a methodology to evaluate permanent concrete barrier systems to MASH 2016 without physical crash testing. Permanent concrete barriers submitted by Midwest Pooled Fund Program member states were reviewed, and the evaluation methodology was applied to determine barrier compliance to MASH 2016 criteria.

1.3 Scope

The scope of the research effort was to perform a literature review and determine a methodology for the evaluation of permanent concrete barriers to the provisions of MASH 2016 without expensive crash testing. A survey was administered to collect permanent concrete barrier standards and specifications from the sponsoring agencies. Permanent concrete barriers were then selected and analyzed according to the established methodology, and evaluations were prepared with justifications for MASH 2016 compliance.

2 LITERATURE REVIEW

2.1 MASH Updates from NCHRP Report 350

MASH overhauled many sections of NCHRP Report 350 to more accurately represent real-world and worst-practical impacts on the current highway system. The overhaul largely affected the test matrices for TL-3 and TL-4 impacts on longitudinal barriers. The effects included, but were not limited to, new test vehicles, more severe impact conditions, and modified evaluation criteria. The MASH test matrices for TL-3 and TL-4 crashes are presented in Table 2 [4].

Table 2. MASH Recommended Test Matrices for TL-3 and TL-4 Longitudinal Barriers [4]

Test Level	Barrier Section [c]	Test No.	Vehicle	Impact Speed [a] mph	Impact Angle [a] deg.	Acceptable IS Range [a] kip-ft	Evaluation Criteria [b]
3	Length-of-Need	3-10	1100C	62	25	≥ 51	A, D, F, H, I
		3-11	2270P	62	25	≥ 106	A, D, F, H, I
	Transition	3-20 [d]	1100C	62	25	≥ 51	A, D, F, H, I
		3-21	2270P	62	25	≥ 106	A, D, F, H, I
4	Length-of-Need	4-10	1100C	62	25	≥ 51	A, D, F, H, I
		4-11	2270P	62	25	≥ 106	A, D, F, H, I
		4-12	10000S	56	15	≥ 142	A, D, G
	Transition	4-20 [d]	1100C	62	25	≥ 51	A, D, F, H, I
		4-21	2270P	62	25	≥ 106	A, D, F, H, I
		4-22	10000S	56	15	≥ 142	A, D, G

a See Section 2.1.2 in MASH 2016 for tolerances on impact conditions.
b See Table 5-1 in MASH 2016.
c See Figure 2-1 and Section 2.3.2 in MASH 2016 for impact point.
d Test is optional in MASH 2016

2.1.1 MASH Test Designation No. 10

Test 10 is intended to test the ability of a barrier to safely contain and redirect small passenger cars. Primary concerns in the test are underride, snagging of wheels, rollover, and head slap. MASH replaced the 820C test vehicle of NCHRP Report 350 with the 1100C test vehicle. This change resulted in an increase in vehicle mass from 1,808 lb to 2,420 lb. The impact angle of the test also increased from 20 to 25 degrees. The speed remained constant at 62 mph. These changes caused the lower limit of the impact severity of the test to rise 102 percent, from 25.2 kip-ft to 51.0 kip-ft. The large increase in impact severity has raised concern over the increased likelihood of snagging, which may contribute to greater occupant compartment deformations.

2.1.2 MASH Test Designation No. 11

Test 11 is a strength test for TL-1 through TL-3. In addition, this test is required for all barrier configurations and test levels due to the high frequency of pickup truck rollovers observed in previous crash testing studies. MASH replaced the 2000P test vehicle of NCHRP Report 350 with the 2270P test vehicle. This change resulted in an increase in vehicle mass from 4,409 lb to 5,000 lb. The impact angle of the test remained constant at 25 degrees. The speed remained constant at 62 mph. These changes caused the nominal impact severity of the test to rise 13 percent, from 102.7 kip-ft to 106.0 kip-ft. The increase in impact severity resulted in greater impact forces than the forces presented in Section 13 of the AASHTO LRFD Bridge Design Specifications [7].

2.1.3 MASH Test Designation No. 12

Test 12 is performed to appraise the ability of a barrier system to resist the forces of a heavy single-unit truck (SUT). MASH replaced the 8000S test vehicle of NCHRP Report 350 with the 10000S test vehicle. This change resulted in an increase in vehicle mass from 17,637 lb to 22,046 lb. The impact angle of the test remained the same at 15 degrees, but the speed increased from 49.7 mph to 56 mph. These changes caused the lower limit of the impact severity of the test to rise 65 percent, from 85.9 kip-ft to 142 kip-ft.

2.1.4 Evaluation Criteria

The evaluation criteria for longitudinal barriers remained principally consistent between NCHRP Report 350 and MASH 2016. Barrier systems are assessed on three main categories: structural adequacy, occupant risk, and post-impact vehicular response. Post-impact vehicular response was referred to as vehicle trajectory under NCHRP Report 350. No changes were made to the structural adequacy criterion under MASH.

A minor change in the occupant risk criteria was the 0.49 g increase in the maximum allowable ridedown accelerations to 20.49 g's in MASH. In addition, MASH established maximum occupant compartment deformations for various locations in a test vehicle. Previously, the test agency was responsible for justifying the risk to occupants due to compartment deformations, and instituting specific deformation criteria eliminated the subjective component of this assessment. The maximum allowable occupant compartment deformations are listed in Section 5.2.2 of MASH and are shown in Table 3.

Table 3. MASH Maximum Allowable Occupant Compartment Deformations

Location	MASH 2016 Allowable Deformation in.
Wheel Well & Toe Pan	≤ 9
Floor Pan & Transmission Tunnel	≤ 12
A-Pillar	≤ 5
A-Pillar (Lateral)	≤ 3
B-Pillar	≤ 5
B-Pillar (Lateral)	≤ 3
Side Front Panel (in Front of A-Pillar)	≤ 12
Side Door (Above Seat)	≤ 9
Side Door (Below Seat)	≤ 12
Roof	≤ 4
Windshield	≤ 3
Side Window	No shattering resulting from contact with structural member of test article

MASH modified the post-impact vehicular response section by redacting Criteria K through M, which previously applied to the TL-3 and TL-4 test matrices for longitudinal barriers under NCHRP Report 350. Criterion K stated a preference that the vehicle's post-impact trajectory not protrude into adjacent traffic lanes. Criterion L contained the OIV and ORA limits for pickup truck impacts, which was moved to Criterion H and I with the small car impact limits. Criterion M stated that exit angle not exceed 60 percent of the impact angle. MASH noted that excessive exit angles are not desirable, and adapted the concept of the "exit box" directly from European Committee for Standardization (CEN) standards. The "exit box" restricts the area in which the test vehicle may exit after impact and the box dimensions are determined from the length and width of the vehicle as seen in Figure 1, which appears as Figure 5-1 in MASH.

Distance for Exit Box Criterion

Vehicle Type	A ft (m)	B ft (m)
Car/Pickup	$7.2 + V_W + 0.16V_L$ ($2.2 + V_W + 0.16V_L$)	32.8 (10.0)
Other Vehicles	$14.4 + V_W + 0.16V_L$ ($4.4 + V_W + 0.16V_L$)	65.6 (20.0)

V_W = Vehicle Width
V_L = Vehicle Length

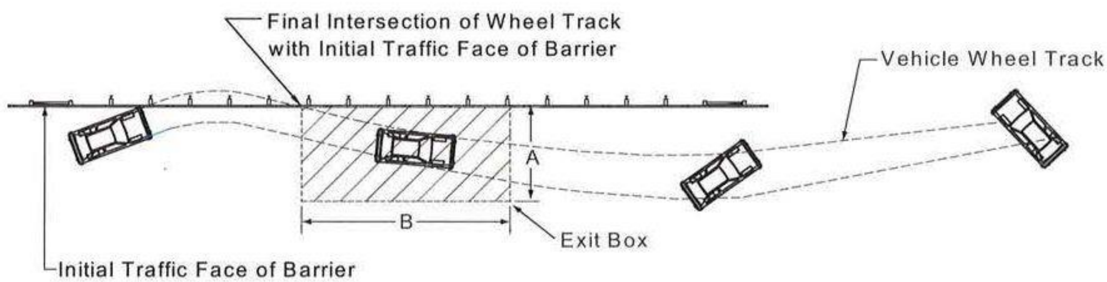

Figure 1. Exit Box for Longitudinal Barriers [4]

2.2 MASH TL-3 Minimum Height, Effective Height, and Design Impact Force Research

Research conducted under NCHRP Project 22-20(02) defined the TL-3 impact load correlating with the new MASH 2270P pickup truck vehicle [8]. The study verified the previously recommended impact force of 54 kips using the commercial finite element (FE) software LS-DYNA [9] to run simulations with the NCHRP Report 350 pickup truck model, the 2000P vehicle. Moving forward, the 2000P model was exchanged for an upgraded 2270P model, and a similar simulation was used to determine the impact load of the MASH vehicle. Using 50-millisecond average forces, the maximum force achieved by the 2270P vehicle on a 32-in. tall vertical barrier was 70 kips, which represented a 30 percent increase from NCHRP Report 350.

As documented in the AASHTO LRFD Bridge Design Specifications, the minimum recommended height for TL-3 barriers under NCHRP Report 350 was 27 in. [7]. In research conducted at the Texas Transportation Institute (TTI) under NCHRP Project 20-07(395), bridge rails of various sizes, shapes, and materials were computationally analyzed to MASH standards. As part of the project, a new minimum rail height for TL-3 impacts was investigated using LS-DYNA [10]. The study simulated pickup truck crash tests into rigid vertical barriers with heights of 27, 28, and 29 in. The 27-in. tall barrier resulted in a rollover. The 28-in. tall barrier did not result in rollover but was deemed to have severe potential for instabilities. Therefore, 29-in. was selected as the minimum MASH TL-3 rail height to maintain test vehicle stability throughout impact.

In addition to TL-3 vehicle stability, the transverse impact force (F_t) and resultant impact height (H_e) were also studied. According to simulations, MASH and NCHRP Report 350 TL-3 pickup truck impacts are expected to generate impact loads of 71 and 61 kips, respectively. The effective load height from the FE simulations was calculated to be 19.5 in. and 18 in. respectively.

2.3 MASH TL-4 Minimum Height, Effective Height and Design Impact Force Research

Since the original publication of MASH, researchers have suspected changes would need to be made to current design methodologies. In recent years, efforts have been made to quantify these changes for the varying test levels. These efforts have included studies performed to identify new minimum barrier heights to prevent vehicle instabilities, and to estimate new design impact forces to ensure structural integrity of barriers.

The first study was published in 2011 by the TTI [11]. Sheikh et al. utilized LS-DYNA to test and identify a minimum height for vehicle stability in MASH TL-4 crashes. As part of the simulations, the SUT model was modified to better represent critical parameters. Chief among the modified parameters was the reduction of track width, which led to a more unstable model and yielded more conservative results.

Sheikh et al. then ran simulations of the SUT model impacting single-slope barriers with heights of 42, 39, 38, 37, and 36 in. in accordance with MASH TL-4 impact conditions. Through an evaluation of the roll, pitch, and yaw angles of the simulations, all barrier heights were deemed sufficient. However, 36 in. was considered to be marginal in the categories of stability and rollover potential, with the rear wheels nearly passing over the top of the barrier, as shown in Figure 2 [11]. Therefore, no further simulations were conducted, and 36 in. was declared the minimum TL-4 barrier height to prevent vehicle instability according to FE simulations.

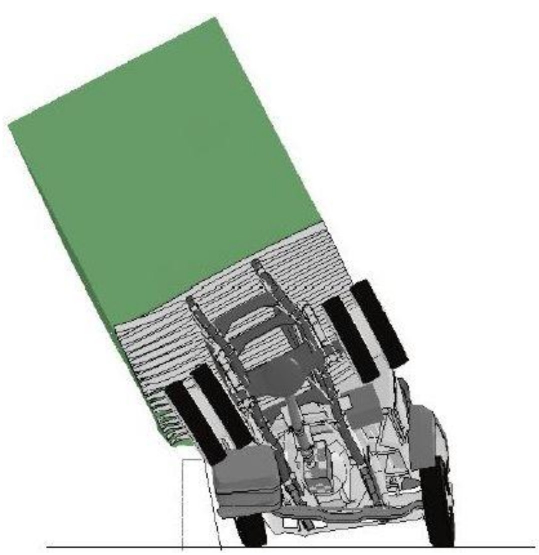

Figure 2. Simulated Impact of SUT on 36-in. Tall Single-Slope Barrier [11]

The results of the FE simulation were verified by conducting MASH test designation no. 4-12 on a Texas Department of Transportation (TxDOT) 36-in. tall Single-Slope Traffic Rail (SSTR) [11]. In test no. 420020-9b the barrier system met MASH criteria. As in the FE simulation, the rear wheels rose near the top of the barrier. It was noted that the crash tested single-slope barrier shape is known to reduce vehicle climb as compared to New Jersey and F-shape barriers due to the presence of a barrier toe. However, due to the larger vehicle mass and wheel radius of the SUT, the effect was expected to be insignificant. With these considerations, 36 in. was recommended to be the minimum TL-4 height for all barrier types.

In addition to minimum barrier height, TL-4 impact forces were studied [11]. Impact forces were determined using LS-DYNA simulations at each of the 36-in. to 42-in. heights previously used for the minimum height determination. The simulations showed that the 50-millisecond average force of initial impact did not increase with height. However, as height increased, the tail-slap impact (i.e., rear axle contact with the barrier due to redirection) increased and became critical. It was noted that the force associated with the recommended minimum height should not be selected as the design force, as barriers may be designed at greater heights that meet TL-4 standards. Therefore, 80 kips was selected as the design force, which corresponds to a 42-in. tall barrier and is the minimum height for a TL-5 barrier [11].

This effort to quantify the peak force and location on TL-4 barriers continued in NCHRP Project 22-20(02), beginning with a simplified dimension analysis of a mass-spring system to estimate a new impact load. This analysis used ratios of the system's stiffness, mass, lateral acceleration, impact angle, and center of mass to calculate an impact load of 80.3 kips for TL-4 crash tests. Another method used to estimate the TL-4 dynamic load was Newton's Second Law of Motion. The total mass of the vehicle multiplied by the lateral acceleration yielded an impact load of 99 kips. Neither method addressed vertical force distribution along a barrier face, and therefore, a resultant height of the force could not be determined, so FE simulations in LS-DYNA were also employed.

The FE simulations were conducted on 36 in., 39 in., 42 in., and "tall" vertical rigid barriers. The "tall" barrier had a height greater than the height of the SUT and was used to determine a maximum transverse force (F_t) for longitudinal barrier impacts. The maximum total transverse impact force for each barrier was quantified as well as the distribution over the height of the barrier. Transverse force distributions over barrier faces were utilized to compute an effective height (H_e) by taking the weighted average of the force over the height of the barrier. The longitudinal impact forces (F_L), longitudinal force distribution length (L_L), vertical impact forces (F_v), and vertical force distribution length (L_v) were also analyzed and estimated from the simulations. The results of the study for TL-4 impacts led to the recommended parameters summarized in Table 4. Impact forces were only determined for barrier heights of 36 in. or greater due to the stability issues observed in earlier research.

Table 4. Recommended Design Parameters for MASH TL-4 Impact [8]

Design Force and Designations	TL-4	
	36-in. Barrier Height	>36-in. Barrier Height
F_t, Transverse	70 kips	80 kips
F_L, Longitudinal	22 kips	27 kips
F_V, Vertical	38 kips	33 kips
L_L	4 ft	5 ft
L_V	18 in.	18 in.
H_e	25 in.	30 in.

2.4 Stand-Alone Foundations

TTI recently conducted FE simulations and crash testing on structurally independent moment slab and concrete beam foundations for the TxDOT SSTR barrier [12]. The SSTR is a 36-in. tall barrier with an 11-degree single-slope traffic face. Preliminary designs were developed for concrete beam, moment slab, and concrete beam-and-slab foundation systems, and a parametric study was conducted to optimize the design of each foundation system. All simulations were conducted in LS-DYNA to MASH TL-4 impact conditions and the native soil properties found at the TTI proving ground testing facility were modeled rather than typical well-compacted soils used in crash testing. Following the parametric study, the preferred moment slab configuration was evaluated in a full-scale MASH TL-4 crash test.

Six concrete beam foundations were simulated with varying section dimensions, segment lengths, and ditch characteristics. The results of the FE simulations conducted on the concrete beam foundations are summarized in Table 5.

The concrete beam foundation with a 30-ft segment length was selected as the most favorable beam foundation design, and TxDOT designed reinforcement details for this option, as seen in Figure 3. The barrier is longitudinally reinforced with eight #4 bars and vertically reinforced with #4 stirrups spaced at 6 in. The foundation measured 16 in. wide and 33 inches deep, and was reinforced with four #5 longitudinal bars and #4 stirrups spaced at 8 in. The barrier is connected to the foundation with #4 U-bars, also spaced at 6 in. The system was detailed to permit the foundation and the barrier to be poured separately.

Table 5. MASH TL-4 FE Simulation Results of Concrete Beam Foundations [12]

Width in.	Depth in.	Segment Length ft	Ditch Slope	Ditch Offset ft	Result
19	33	15	1V:2H	0	Unacceptable barrier deflection and test vehicle was not contained or redirected
19	33	20	1V:2H	0	Test vehicle was not redirected or contained
19	33	20	1V:2H	1	Test vehicle was not redirected or contained
16	33	30	1V:2H	1	Barrier performed acceptably
18	27	50	N/A	N/A	Barrier performed acceptably
13	10	50	N/A	N/A	Barrier performed acceptably

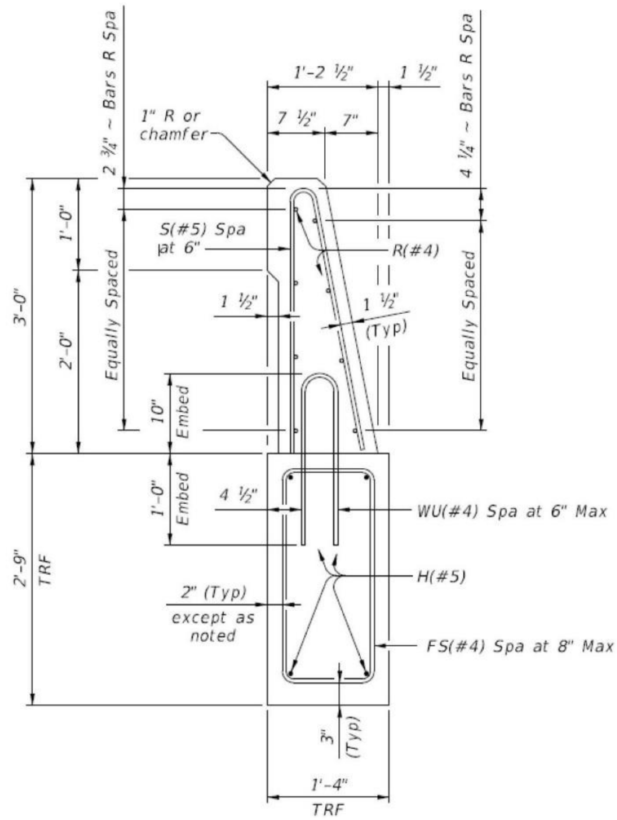

Figure 3. Reinforcement Details for TxDOT SSTR with Concrete Beam Foundation [12]

Three moment slab foundations were simulated with varying section dimensions, segment lengths, and ditch characteristics. The moment slab simulation results are summarized in Table 6. Smaller segment lengths were preferred for ease of casting and handling, therefore, the moment slab foundation with a 20-ft length was selected as the most favorable design. Reinforcement details were determined, and the system underwent full-scale crash testing. In test no. 469689-3-3, the moment slab foundation with a 36-in. TxDOT SSTR barrier was crash tested to MASH test designation no. 4-12. The concrete barrier was vertically reinforced with #4 stirrups spaced at 6 in. and longitudinally reinforced with four #4 bars on both the front and back sides of the barrier. The barrier was anchored to the 12-in. deep by 60-in. wide moment slab by #4 U-shape bars spaced longitudinally at 6 in. All occupant risk factors were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 4-12 [12].

Table 6. MASH TL-4 FE Simulation Results of Concrete Moment Slab Foundations [12]

Width in.	Depth in.	Segment Length ft	Ditch Slope	Soil Restraint in.	Result
36	8	50	N/A	8	Barrier performed acceptably
60	12	15	N/A	0	Excessive barrier deflection Test vehicle was not redirected or contained
60	12	20	N/A	12	Barrier performed acceptably

Two hybrid concrete beam and slab foundations underwent FE simulation. After the first simulation produced an acceptable result, section dimensions were reduced, and crash testing was again simulated. The second simulation also produced acceptable results, and the more critical dimensions of the second simulation are reported in Table 7.

Table 7. MASH TL-4 FE Simulation Result of Concrete Beam and Slab Foundation [12]

Width	Depth	Segment Length	Ditch Slope	Soil Restraint	Result
31.3 in.	12 in.	Not Reported	N/A	12 in.	Barrier performed acceptably

Additional TL-4 FE simulations were conducted on the TxDOT SSTR barrier on top of a stand-alone retaining wall configuration [13]. The barrier and retaining wall dimensions are shown in Figure 4. The simulations resulted in soil pressures of 20 psi, which was greater than the allowable soil pressure of 12.2 psi. However, due to the dynamic nature of an impact load being applied over a short time period, Williams et al. asserted that these pressures would not cause significant performance issues. Therefore, the FE simulations led to the conclusion that a barrier on top of a retaining wall would be stable when impacted under MASH TL-4 conditions, but it was also recommended to conduct further simulations to confirm these findings.

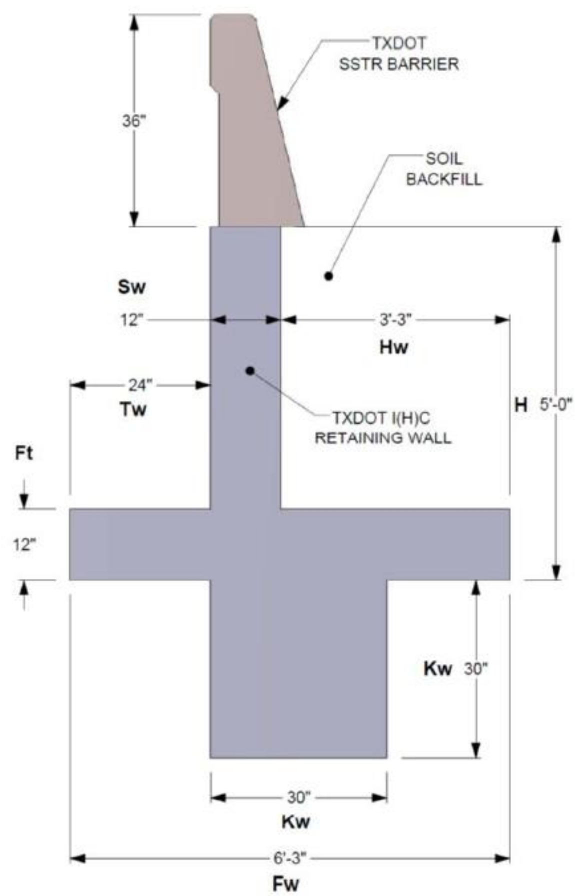

Figure 4. TxDOT SSTR Retaining Wall Foundation [13]

2.4.1 Moment Slab and Wall Coping Analysis

Moment slab and wall coping anchorage systems have been tested to MASH test designation nos. 3-11 and 4-12 under test nos. 475350-1 [14] and 510602-EWP1 [15], respectively. Test no. 475350-1 was conducted on a 32-in. tall precast vertical barrier with a cast-in-place moment slab, as shown in Figure 5. The moment slab featured five #4 longitudinal bars near the top of the slab and was connected to the precast barrier via #6 L-shaped bars spaced longitudinally at 10 in. Joints in the moment slab were spaced at 30 ft. The barrier system met the evaluation criteria of MASH test designation no. 3-11.

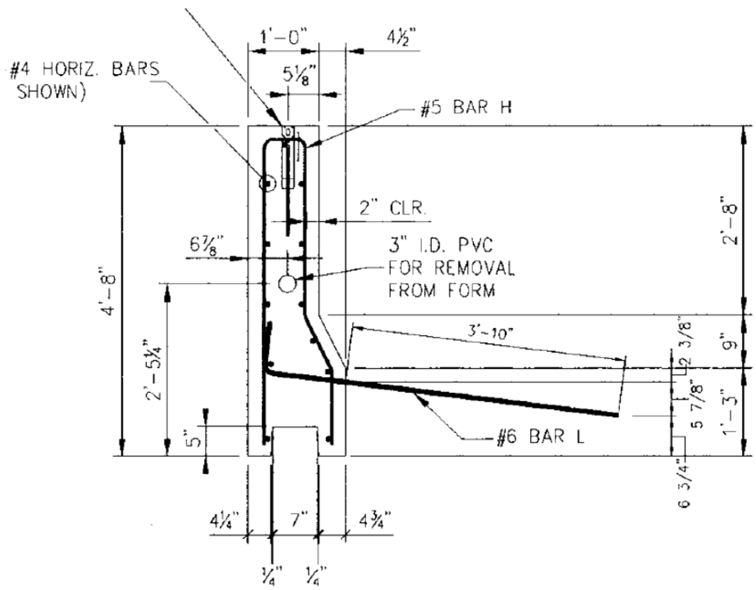

Figure 5. Test No. 475350-1 Moment Slab and Wall Coping Dimensions [14]

Test no. 510602-EWP1 was a crash test performed on the GRAVIX® barrier, a proprietary precast barrier and moment slab assembly manufactured by Earth Wall Products, LLC [15]. The GRAVIX® barrier currently holds FHWA Eligibility Letter B-249 for compliance with MASH TL-4 crash testing. However, due to Earth Wall Product's proprietary rights, details of the barrier are limited except for the overall shape.

Research conducted under NCHRP Projects 22-20 and 22-20(2) [8, 14] established design guidelines for moment slabs subjected to MASH impacts, including the minimum widths summarized in Table 8, and calculation criteria for sliding and overturning limit states. In addition to providing the minimum width, the moment slab length must be at least 20 ft and the joints between slabs must be joined with a minimum of two #9 steel dowels to transfer loads.

Table 8. Minimum Width for MASH TL-3 and TL-4 Moment Slab Anchorage [8]

Test Level	TL-3	TL-4
Width	≥ 4 ft	≥ 4.5 ft

Notes:
Moment slab length must be ≥ 20 ft
Joints joined by at least two #9 steel dowels

NCHRP Project 22-20(02) recognized two limit states for barriers in a moment slab configuration: sliding and overturning. The sliding limit state is evaluated according to Equation 1 below, in which the factored static resistance (φP) must be greater than or equal to the factored equivalent static load (γL_s). The equivalent static load was investigated for each test level and the results are presented in Table 9.

$$\varphi P \geq \gamma L_s \tag{1}$$

Table 9. Equivalent Static Loads for MASH TL-3 and TL-4 Moment Slab Design [8]

Test Level	TL-3	TL-4
L_s	23 kip	28 kip

The overturning limit state is evaluated using Equation 2 below, according to the results of NCHRP Project 22-20(2). The equation requires the factored moment resistance of the barrier-slab system (φM) to be greater than or equal to the moment induced by the equivalent static load.

$$\varphi M \geq \gamma L_s(h_A \text{ } or \text{ } h_B) \tag{2}$$

The moment arm (h_A *or* h_B) was found to vary depending on the expected rotation of the barrier during overturning. Barriers with moment slabs tended to rotate about one of two locations, identified as points A and B in Figure 6. The barrier will rotate about point A when the top of the mechanically stabilized earth (MSE) wall is isolated from impact with the coping. The isolation can be created by an air gap or adequate condensable material. The barrier will rotate about point B if the wall coping sits directly atop the MSE wall panel.

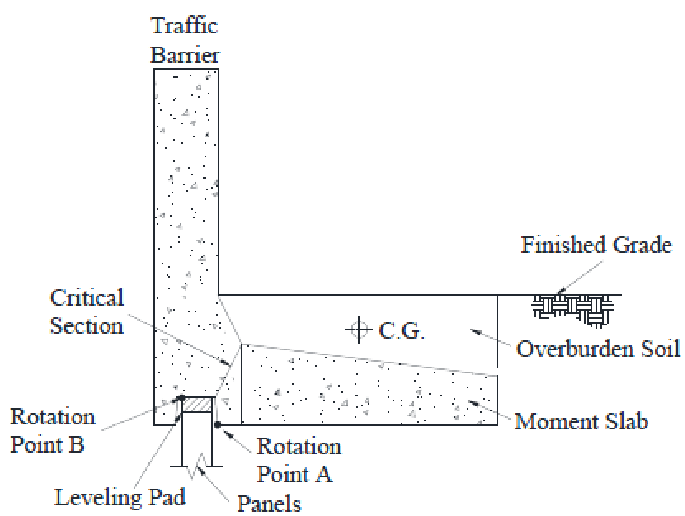

Figure 6. Points of Rotation for Overturning Barrier-Moment Slab Systems [8, 14]

2.5 Grade Separated Barriers

A grade separated barrier is a barrier in which the elevations of the surfaces on opposite sides of the barrier differ. A cross-section of an example grade separated barrier from the Minnesota Department of Transportation Standard Details is displayed in Figure 7.

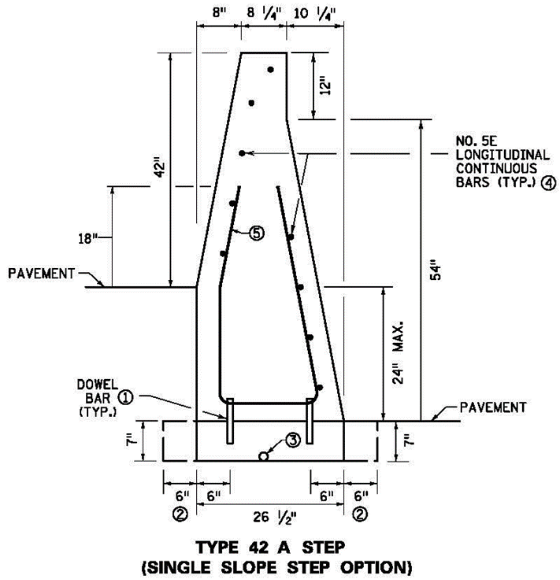

Figure 7. Minnesota Type 42 A Grade Separated Barrier Example [16]

A design of a 112½-in. tall grade separated barrier was researched and developed by TTI [17]. An original design submitted by the Tennessee Department of Transportation featured a split single-slope median wall design, but analyses were conducted on several different barriers: (1) a grade separated 112½-in. tall single-slope median barrier, (2) a 51-in. tall single-slope median barrier, (3) a 112½-in. tall grade separated vertical barrier with a single-slope back face, and (4) a 51-in. tall vertical barrier with single-slope back face. A simulation of MASH test designation no. 3-11 was performed on an 80-ft section of all four barrier configurations. All four barriers were observed to adequately contain and redirect the 2270P vehicle and were deemed to be satisfactory to MASH test designation no. 3-11.

Additional segment length optimization simulations were performed to MASH test designation no. 4-12 on barriers (1) and (2) described above. These simulations were performed on a 35 ft section of the 112½-in. tall grade separated single-slope median barrier and a 60-ft section of the 51-in. tall single-slope median barrier. In both cases, the barriers were deemed to have adequately contained and redirected the 10000S test vehicle. However, when the simulation ended for the 51-in. tall barrier, the barrier was still displacing backward. Silvestri-Dobrovolny et al. believed that the additional movement was minor and did not pose a threat of intruding into the opposing lane. Additionally, the simulation was considered conservative due to not modeling a 1½-in. thick asphalt keyway anchorage typically used in the design and modeling a 1½ in. reduced height of the barrier design. Therefore, Silvestri-Dobrovolny et al., concluded that the 51-in. tall, single-slope median barrier had met MASH evaluation criteria.

An additional segment length optimization simulation was performed to MASH test designation no. 3-11. The simulation was performed on a 24-ft section of the 112½-in. tall grade separated single-slope median barrier. The simulation resulted in the barrier adequately containing and redirecting the 2270P vehicle.

In addition to the FE simulations, some of the barriers were also computationally evaluated for sliding, overturning, bearing capacity, and strength. The strength was evaluated through a yield line analysis. Based on the results of the FE simulations and computational analysis, Silvestri-Dobrovolny et al. provided recommendations for the minimum segment lengths of each barrier type.

2.6 Post-and-Beam Barriers

Section 13 of the AASHTO LRFD Bridge Design Specifications [7] provides plots in A13.1.1-2 and A13.1.1-3 to assess the shapes of post-and-beam barriers. These plots, reproduced in Figures 8 and 9, provide guidance on the relationship between barrier geometry and the potential for impact with a post that could lead to excessive damage to the vehicle and risk to the occupant. The plots are based on post setback distance, vertical clear opening, and the ratio of contact width to total height.

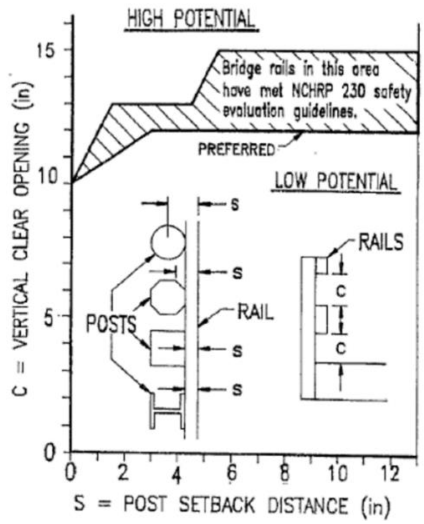

Figure 8. Potential Impact of Post with Wheel, Bumper or Hood [7]

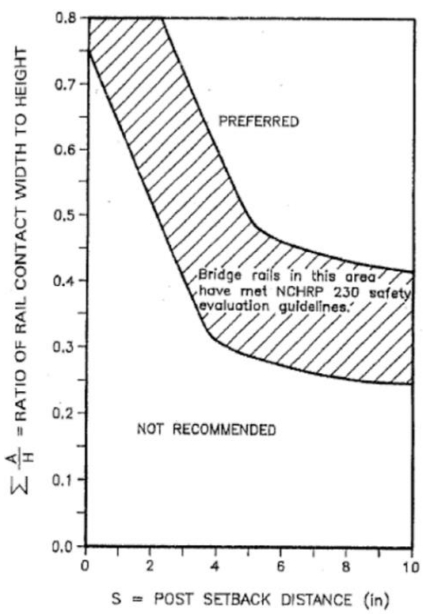

Figure 9. Post Setback Criteria [7]

Although these plots, originally developed under NCHRP Report 230 guidelines, are somewhat archaic, NCHRP Project 20-07(395) indicated these plots may remain relevant for crashworthiness assessments of post-and-beam and other similar systems [10]. In some instances, systems that plotted in the hatched regions or even in the "not recommended" spaces of Figures 8 and 9 did still meet the requirements of crash tests. However, this behavior was erratic. All NCHRP Report 350 or MASH tests that plotted in both the "low potential" region of Figure 8 and the "preferred" region of Figure 9 met the applicable safety performance criteria. The research results are summarized in Table 10 and illustrated in Figures 10 through 13. Therefore, in NCHRP Project 20-07(395), a successful evaluation of a post-and-beam barrier required the barrier to plot in the "low potential" area of Figure 8 and the "preferred" area of Figure 9.

Table 10. Concrete Beam-and-Post Rail Systems and Geometry [10]

Bridge Rail System	MASH or NCHRP Report 350	Post Setback Distance in.	Vertical Clear Opening in.	Ratio of Contact Width to Height
TxDOT T223 Bridge Rail	MASH	4.5	13.0	0.60
TxDOT T224 Bridge Rail	MASH	3.5	12.0	0.70
T202 Bridge Rail	NCHRP Report 350	1.5	13.0	0.52
Modified T202 Bridge Rail	NCHRP Report 350	4.5	13.0	0.52
Natchez Trace Bridge Rail	NCHRP Report 350	2.0	9.5	0.71
Nebraska Open Bridge Rail	NCHRP Report 350	2.0	13.0	0.55
Type 80SW Bridge Rail	NCHRP Report 350	4.0	11.0	0.65

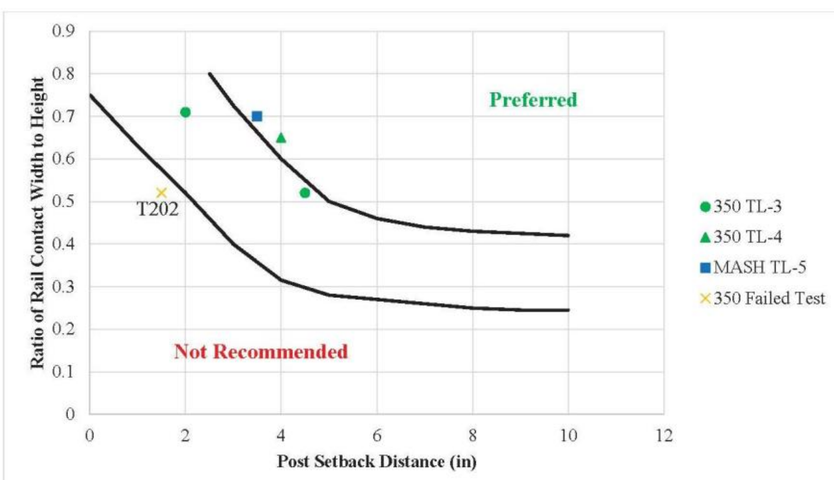

Figure 10. MASH and NCHRP Report 350 Passenger Car Post-and-Beam Data: Ratio of Contact Width to Height vs. Post Setback [10]

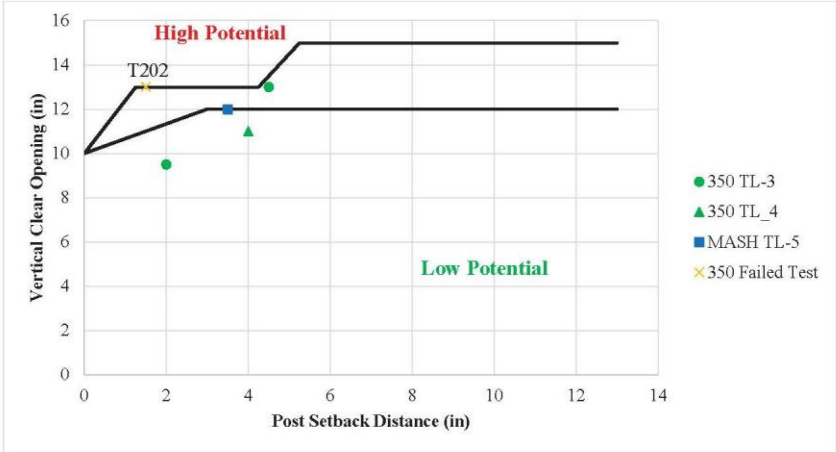

Figure 11. MASH and NCHRP Report 350 Passenger Car Post-and-Beam Data: Vertical Clear Opening vs. Post Setback [10]

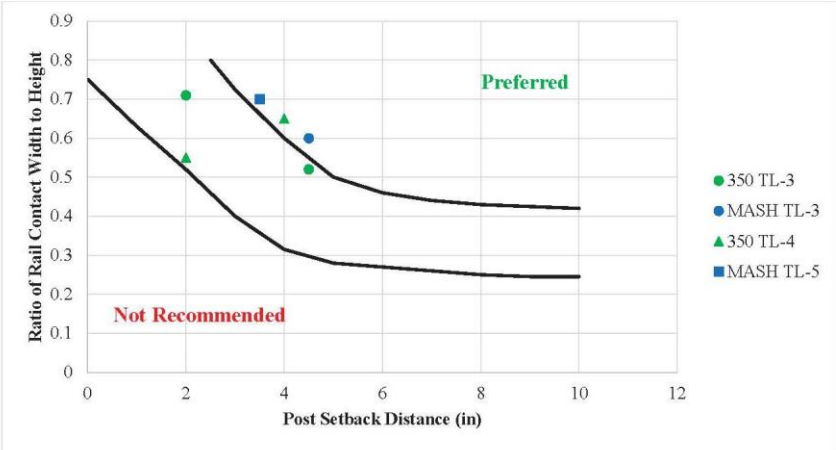

Figure 12. MASH and NCHRP Report 350 Pickup Truck Data: Ratio of Contact Width to Height vs. Post Setback [10]

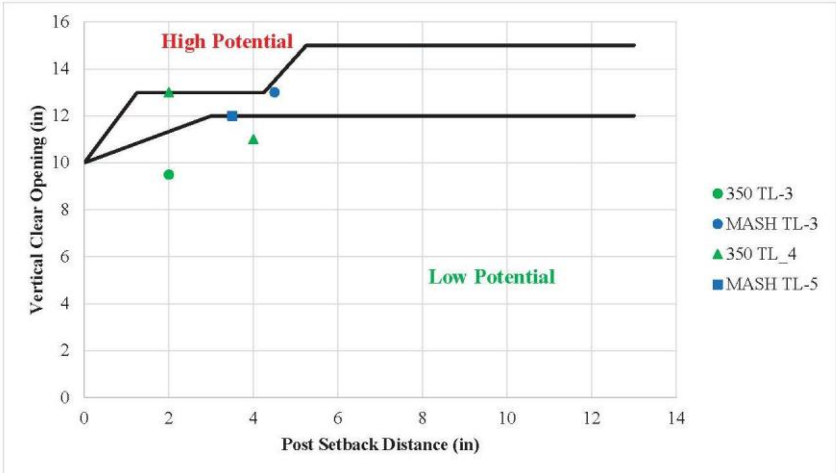

Figure 13. MASH and NCHRP Report 350 Pickup Truck Data: Vertical Clear Opening vs. Post Setback [10]

2.7 Textured and Aesthetic Barriers

Textured and aesthetic barriers feature a facing without a smooth finish. The texturing is applied as an aesthetic finish to improve the appearance of the roadside safety feature. Many textured barriers have been crash tested in accordance with NCHRP Report 350 by the California Department of Transportation in FHWA/CA/TL-2002/03 [18]. The report documented eight NCHRP Report 350 crash tests: three tests conducted according to test designation no. 3-10, and five tests conducted according to test designation no. 3-11. Based on the crash test data, architectural guidelines for single-slope and vertical textured barriers were determined. Suggestions included:

(1) Sandblast textures must have a maximum textural relief of ⅜ in.

(2) Images and patterns inset into a barrier face must have a maximum depth of 1 in. and must contain chamfered or beveled edges of 45 degrees or flatter to prevent wheel snagging.

(3) Texture and patterns of any length and shape may be inset into the barrier face without chamfering the edges up to a maximum depth of ½ in., but the width must be limited to a maximum of 1 in.

(4) A texture featuring gradual undulations must conform to a maximum relief of ¾ in. over a length of 11¾ in.

(5) Gaps, slots, grooves, and joints may have a maximum width of ¾ in. with a maximum surface differential of 3/16 in.

(6) No textures or patterns shall have any long upward-sloping edges or ridges which may induce vehicle climb.

(7) Patterns beginning 24 in. from the base of the barrier and extending to the top of the barrier may have a maximum relief of 2½ in., but leading edges must be rounded or sloped to minimize propensity for snagging. No part of the texture located above 24 in. may protrude past the plane of the lower portion of the barrier.

These guidelines were reported in NCHRP Report 554, *Aesthetic Concrete Barrier Design*, for single-slope and vertical barriers [19]. The report also provided a plot to assess the crashworthiness of asperities in the traffic face of safety shape barriers, as seen in Figure 14. The plot is based on the internal energy of the floorboard rather than occupant compartment deformation. However, these guidelines were developed for NCHRP Report 350 impact severities, and the increased impact severities in MASH may require more stringent regulations of textures and aesthetic features.

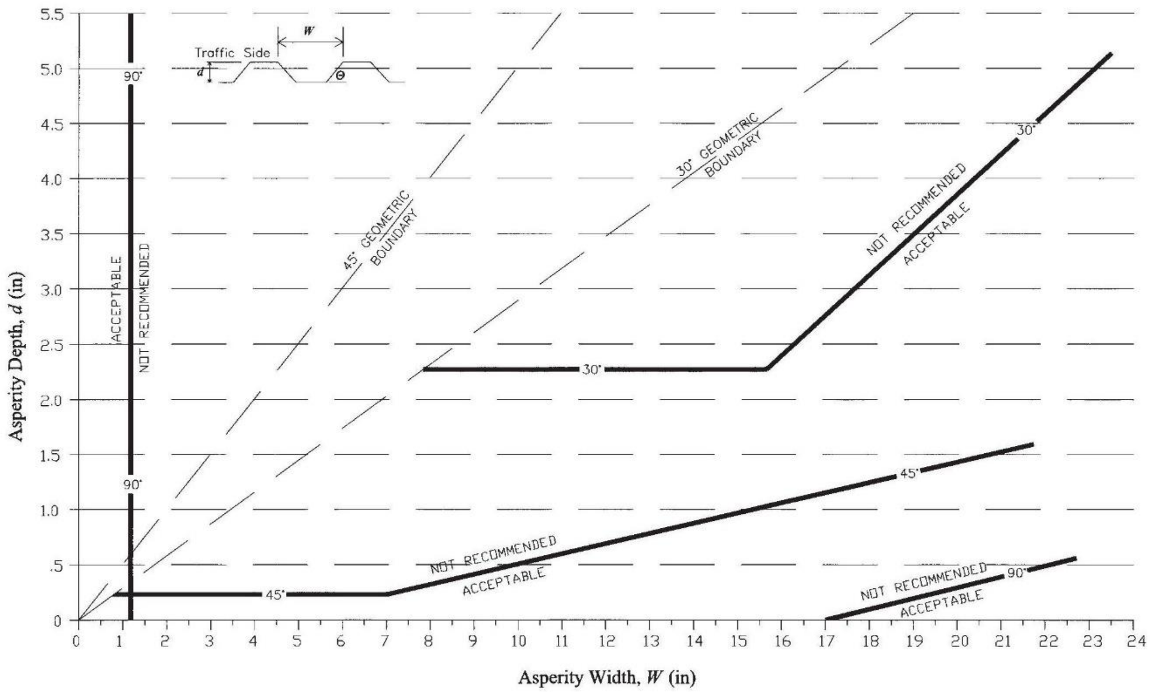

Figure 14. Design Guidelines for Aesthetic Surface Treatment of Safety Shape Concrete Barrier [19]

Four MASH TL-3 crash tests were recently performed on barriers with aesthetic surface treatments [20–21]. The testing was conducted on two barriers, both with a ½-in. inlay. In test nos. H34BR-1 and H34BR-2, the barrier had a 26.6-degree beveled edge and an asperity width of 60 in., which plots in the acceptable range of Figure 14. In test nos. H42BR-1 and H42BR-2, the barrier had a 63.4-degree beveled edge and an asperity width of 6 in. This barrier is more difficult to plot according to Figure 14, and it could be close to the "not recommended/acceptable" limit for the specified angle. However, both aesthetic barriers were deemed crashworthy to MASH TL-3 standards. Therefore, it appears that the guidance in NCHRP Report 554 may still hold relevance for MASH evaluations but could be revisited to establish better guidelines.

2.8 Crash Testing Database

A crash testing database was compiled of 120 crash tests. The database was populated with crash tests conducted according to various standards: six NCHRP Report 230 crash tests, 21 AASHTO Guide Specifications for Bridge Railings crash tests, 52 NCHRP Report 350 crash tests, and 41 MASH crash tests. Details of the MASH crash tests compiled within the database and used for evaluations are provided below.

2.8.1 MASH Single-Slope Barrier Crash Tests

In test no. OSSB-1, a 42-in. tall, 10.9-degree single-slope concrete barrier was crash tested to MASH test designation no. 3-11 [22]. The concrete barrier was entirely unreinforced and was anchored by a 1-in. thick by 8-ft wide asphalt keyway. The crash test resulted in negligible permanent set displacement, and all occupant compartment deformations were within the allowable limits established in MASH. The barrier successfully contained and redirected the barrier according to MASH test designation no. 3-11 [22].

In test no. 140MASH3C16-04, a 36-in. tall, 9.1-degree single-slope concrete barrier was crash tested to MASH test designation no. 3-10 [23]. The section was longitudinally reinforced with four #5 bars on both the front and back sides of the barrier, and was vertically reinforced at the ends with #4 stirrups spaced at 6 in. The end anchorage consisted of a 10-in. deep by 9.8-ft long footing reinforced longitudinally by four #5 bars. Damage to the barrier was minimal, and all occupant risk values were within MASH limits. The barrier successfully contained and redirected the vehicle according to test designation no. 3-10 [23].

In test no. 420020-9b, a 36-in. tall barrier with an 11-degree single-slope traffic face was crash tested to MASH test designation 4-12 [11]. The section was longitudinally reinforced with five rows of two 0.4-in. diameter welded wire reinforcement (WWR) and vertically reinforced with ⅜-in. diameter WWR spaced at 6 in., respectively. The barrier was fixed to a slab with #4 stirrups spaced at 6 in. on center. The barrier had cosmetic damage only, and all occupant risk values were within MASH limits. The barrier successfully contained and redirected the barrier according to test designation no. 4-12 [11].

In test nos. 469467-3-1 and 610221-01-1, a 42-in. tall barrier with a 10.8-degree single-slope traffic face was crash tested to MASH test designation no. 4-12 [24–25]. The section was reinforced with 6 x 8–D20 x D9 welded wire reinforcement bent into a U-shape. The system was anchored with a 1-in. thick by 9-in. wide asphalt keyway. The segment lengths were 75 ft for test no. 469467-3-1 and 40 ft for test no. 610221-01-1. In both tests, the barrier experienced minimal damage, negligible permanent set deflection, and all occupant risk values were within MASH limits. The barriers successfully contained and redirected the barrier according to test designation no. 4-12 [24–25].

In test no. 510602-EWP1, a 36-in. tall barrier with an 11-degree single-slope traffic face was crash tested to MASH test designation no. 4-12 [15]. The barrier consisted of 8-ft precast sections with an unspecified amount of reinforcement. Each precast section had an 18-in. thick by 8-ft. long moment slab wall coping system and resulted in a 1¼-in. permanent set deflection. All occupant risk factors were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 4-12 [15].

In test no. 490027-2-1, a 42-in. tall barrier with a 10.8-degree single-slope traffic face was crash tested to MASH test designation no. 4-12 [26]. The barrier consisted of 30-ft precast sections reinforced with 6 x 14–D22 x D20 welded wire reinforcement bent into a U-shape. The barrier system was anchored by a 13-in. tall slot at the bottom of the section. The slot was fitted over #8 rebar embedded 5¼ in. into the deck using Hilti RE-500 V3 epoxy. The #8 bars were spaced at 72 in. and protruded 12 in. above the concrete deck. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 4-12 [26].

In test no. MAN-1, a 49¼-in. tall barrier with a 9.1-degree single-slope traffic face was crash tested to MASH test designation no. 5-12 [27]. The barrier was vertically reinforced with M20 rebar spaced longitudinally at 15¾ in., and longitudinally reinforced by five M15 bars on both the front and back sides of the barrier. The barrier was anchored to a bridge deck by M15

U-shape bars spaced at 15¾ in. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 5-12 [27].

In test no. 420020-3, a 36-in. tall barrier with an 11-degree single-slope traffic face was crash tested to MASH test designation no. 3-11 [28]. The barrier was reinforced with 6 x 6-D11 x D14 welded wire reinforcement bent into a U-shape. The barrier was anchored to a pan-formed bridge deck using 1-in. diameter threaded rods that were embedded into the barrier and bolted to the bottom of the deck. Anchorage was also provided near the non-traffic face by #4 bars epoxied using Hilti HIT RE-500 epoxy. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11 [28].

In test no. 469468-6-1, a 42-in. tall barrier with a 10.8-degree single-slope traffic face was crash tested to MASH test designation no. 4-12 [29]. The barrier was reinforced with 6 x 8-D20 x D9 welded wire reinforcement bent into a U-shape. The barrier was anchored to a concrete deck using two #6 L-shaped bars spaced at 12 in. Anchorage was also provided by a 1-in. by 9-ft asphalt keyway on both sides of the median barrier. The system also featured a light pole mounted to the top of the barrier. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 4-12 [29].

In test no. 405160-13-1, a 32-in. tall barrier with a 10.8-degree single-slope traffic face was crash tested to MASH test designation no. 3-11 [30]. The barrier was vertically reinforced with #4 longitudinal bars spaced at 12 in., and longitudinally reinforced with five #5 bars on both the front and back sides of the barrier. The barrier was cast in 20-ft long sections connected by grouted rebar-grid slot connections. Anchorage was provided by a 10-in. deep soil keyway. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11 [30].

In test no. 4CBR-1, a 36-in. tall barrier with a 2.9-degree single-slope traffic face was crash tested to MASH test designation no. 4-12 [31]. The barrier was vertically reinforced with #4 stirrups longitudinally spaced at 12 in., and longitudinally reinforced with four #5 bars on both the front and back sides of the barrier. Anchorage was provided by embedding the vertical #4 stirrups into the concrete deck. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 4-12 [31].

2.8.2 MASH Vertical Barrier Crash Tests

In test nos. 130MASH3C13-02, 130MASH3P13-01, and 110MASH2C14-01, a 32-in. tall vertical barrier was crash tested to MASH test designation nos. 3-10, 3-11, and 2-10, respectively [32]. The barrier was vertically reinforced with two #5 L-bars spaced longitudinally at 8 in. and 16 in. The longitudinal reinforcement consisted of six #5 bars on both the front and back faces of the barrier. The barrier also included a 14-in. tall by 12-in. wide top beam and a metal pedestrian handrail atop the barrier. Anchorage was provided by extending the vertical reinforcement into the concrete deck. The tested system included an 8-in. tall elevated sidewalk cast in front of the barrier [32]. Note, the 32-in height was measured from the top of the elevated sidewalk.

In test nos. 130MASH3P13-01 and 110MASH2C14-01, all occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation nos. 3-11 and 2-10, respectively [32].

In test no. 130MASH3C13-02, the recorded ridedown accelerations originally appeared to be larger than the limits established by MASH. The increased accelerations were believed to have been caused by the presence of the sidewalk reducing the flail space of the occupant before contact with the barrier. However, after further investigation conducted under an Interlaboratory Comparison (ILC) through AASHTO Task Force 13 (TF13), ridedown accelerations were determined to have been incorrectly calculated from the time when the vehicle struck the sidewalk curb. The ridedown accelerations should have been calculated starting at contact with the barrier. After the correction of the error, AASHTO TF13 determined the test to be successful according to MASH test designation no. 3-10 [32].

In test no. 469467-1-1, a 36-in. tall vertical barrier was crash tested to MASH test designation no. 4-12 [24]. Longitudinal and vertical reinforcement were provided by 6 x 6-D17 xD17 welded wire reinforcement bent into a U-shape. The system was anchored to a concrete deck utilizing #4 U-bars spaced at 6 in. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 4-12 [24].

In test no. 490024-2-1, a 32¾-in. tall vertical barrier was crash tested to MASH test designation no. 3-11 [33]. The barrier was vertically reinforced with #4 stirrups spaced longitudinally at 6 in. Longitudinal reinforcement in the barrier was provided by four rows of two #4 bars. The barrier was unconventionally anchored to the bridge deck by a ¾-in. thick steel plate bolted through the deck. The plate was welded to five #5 bars that were embedded into sections of the barrier. The plate-bar anchorage configurations were longitudinally spaced at 48 in. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11[33].

In test no. 475350-1, a 32-in. tall vertical barrier was crash tested to MASH test designation no. 3-11 [14]. The barrier was vertically reinforced with alternating #5 bars spaced at 10 in. Longitudinal reinforcement was provided by five rows of two #4 bars. The system was anchored by a 15-in. tall by 10-ft wide moment slab and wall coping. The moment slab was covered by 9 in. of soil and was connected to the barrier section by #6 L-shaped reinforcing bars spaced at 10 in. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11 [14].

In test nos. H34BR-1 and H34BR-2, a 34-in. tall aesthetic barrier was crash tested to MASH test designation nos. 3-10 and 3-11, respectively [20]. The barrier was vertically reinforced by two #5 longitudinal bars spaced at 6 in. on the traffic side and 12 in. on the non-traffic side. The vertical reinforcement extended 8 in. into the concrete deck to provide anchorage to the system. Longitudinal reinforcement was provided by four rows of two #5 reinforcing bars. In test nos. H34BR-1 and H34BR-2, all occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicles according to MASH test designation nos. 3-10 and 3-11 [20].

In test nos. H42BR-1 and H42BR-2, a 42-in. tall vertical barrier with asperities was crash tested to MASH test designation nos. 3-10 and 3-11 [21]. The barrier was vertically reinforced with two #5 longitudinal bars spaced at 6 in. and 12 in. on the traffic-face and non-traffic face, respectively. Longitudinal reinforcement was provided by four rows of two #5 bars spaced vertically at 12 in. The system was anchored by extending the vertical reinforcement 8 in. into the concrete. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation nos. 3-10 and 3-11 [21]

2.8.3 MASH New Jersey Barrier Crash Tests

In test nos. 2214NJ-1 and 2214NJ-2, a 32-in. tall, New Jersey barrier was crash tested to standards equivalent to MASH test designation nos. 3-10 and 4-12, respectively [34–35]. The barrier was vertically reinforced with #5 stirrups spaced longitudinally at 8 in. Longitudinal reinforcement was provided by four rows of #8 reinforcing bars. Test nos. 2214NJ-1 and 2214NJ-2 were performed before the publication of MASH 2009, but test parameters were similar to the requirements that were later published within MASH with one exception. It does not appear that the SUT test vehicle in 2214NJ-2 utilized the ballast per MASH 2016 standards. However, the mass of the SUT was 22,047 lb, which falls in the acceptable range for the 10000S test vehicle in MASH 2016.

In test no. 2214NJ-1, all occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-10 [34]. In test no. 2214NJ-2, the test vehicle rolled over the top of the barrier, landing on its side on the non-traffic face side of the barrier. The observed failing behavior was attributed to insufficient height of the barrier to contain and redirect the vehicle. Therefore, test no. 2214NJ-2 was not deemed crashworthy to MASH test designation no. 4-12 [35].

In test no. 401761-SBG1, a 42-in. tall, New Jersey barrier was crash tested to MASH test designation no. 5-12 [36]. The barrier was vertically reinforced by two 12-mm (0.5-in.) diameter glass fiber reinforced polymer (GFRP) reinforcing bars spaced longitudinally at 300 mm (11.8 in.). Longitudinal reinforcement was provided by five rows of two 16-mm (0.6-in.) diameter GFRP reinforcing bars. The system was anchored by extending the vertical reinforcement 195 mm (7.7 in.) into the concrete deck. Additional anchorage was provided by a headed 16-mm (0.6-in.) diameter GFRP reinforcing bar running parallel to the lower, sloped section of the barrier. The headed end of the bar was cast into the deck. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 5-12 [36].

In test nos. 476460-1-4 and 476460-1b, a 32-in. tall, New Jersey barrier was crash tested to MASH test designation nos. 3-11 and 4-12, respectively [37]. The barrier was vertically reinforced with #5 stirrups placed longitudinally at 8 in. Longitudinal reinforcement was provided by four rows of two #4 reinforcing bars. Anchorage was provided by embedding the vertical reinforcement into the concrete deck below. In test no. 476460-1-4, all occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11. In test no. 476460-1b, the test vehicle rolled over the top of the barrier and attained a maximum roll angle of 101 degrees before the test vehicle reached the end of the barrier and the vehicle was able to right itself. However, Bullard et al.

believed that the test vehicle would have continued to roll over the top of the barrier if the test article had had additional length. Therefore, test no. 476460-1b was deemed not crashworthy to MASH test designation no. 4-12 [37].

2.8.4 MASH F-Shape Barrier Crash Tests

In test no. 469467-5-1, a 32-in. tall, F-shape barrier was crash tested to MASH test designation no. 3-11 [29]. The barrier consisted of 30-ft long precast sections with an unreported amount of reinforcement. The segments were connected to adjacent sections by J-J Hooks® end hooks. The precast sections were each anchored by four 1¼-in. diameter pins placed into sleeves in the traffic face toe of the barrier. The pins were driven 5½ in. into unreinforced concrete deck at an angle of 40 degrees from horizontal. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11 [29].

2.8.5 MASH Miscellaneous Barrier Crash Tests

In test nos. 490025-2-3, 490025-2-2, and 490025-2-1, a 42-in. tall post-and-beam barrier was crash tested to MASH test designation nos. 5-10, 5-11, and 5-12, respectively [38]. The barrier had a 9-in. tall curb section and a 21-in. tall beam placed on posts. The post sections were 12 in. tall and were 32 in. wide on the traffic face. The sides of the post were tapered to increase the post setback and reduce the potential for vehicle snag. The curb was anchored to the deck with #5 V-shaped bars spaced longitudinally at 12 in. Each interior post was vertically reinforced with #5 bars spaced at 6 in. on the traffic face and 12 in. on the non-traffic face. The beam section was longitudinally reinforced with five rows of two #6 reinforcing bars confined by #5 stirrups spaced at 6 in. In test nos. 490025-2-3, 490025-2-2, and 490025-2-1, all occupant risk factors were within MASH limits, and the barrier successfully contained and redirected the test vehicles according to MASH test designation nos. 5-10, 5-11, and 5-12 [38].

In test nos. 607451-1, 607451-2, and 607451-3, a 44-in. tall Pulaski Skyway Bridge Parapet was crash tested to MASH test designation nos. 4-10, 4-11, and 4-12, respectively [39]. The barrier featured an 18-in. tall curb and 7-in. tall beam placed atop 8-in. wide posts spaced at 14 in. on center. The curb was anchored to the concrete deck by #5 and #6 bent reinforcing bars and longitudinally reinforced by five #5 reinforcing bars. Each interior post was vertically reinforced by two #6 stirrups. The beam was longitudinally reinforced with three #5 reinforcing bars confined by #3 stirrups spaced at 6 in. In test nos. 607451-1, 607451-2, and 607451-3, all occupant risk values were within MASH limits, and the barrier successfully contained and redirected the tests vehicles according to MASH test designation nos. 4-10, 4-11, and 4-12 [39].

In test no. 420021-5, a 32-in. tall post-and-beam barrier was crash tested to MASH test designation no. 3-11 [40]. The barrier consisted of 4-ft long by 9½-in. wide by 13-in. tall posts and a 15½-in. wide by 19-in. tall beam placed atop the posts. The beam was longitudinally reinforced with four rows of two #5 bars confined by #3 stirrups spaced at 6 in. The posts were vertically reinforced by #5 stirrups extending into the beam above and spaced longitudinally at 3½ in. The posts were anchored by #5 U bars, also spaced at 3½ in. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 3-11 [40].

In test no. 469468-2-1, a 42-in. tall aesthetic barrier was crash tested to MASH test designation no. 5-12 [29]. The barrier consisted of a 17½-in. wide by 18-in. tall curb parapet and 12¼-in. wide by 18-in. tall posts that supported a 17½-in. wide by 6-in. tall beam. The curb parapet was anchored to the concrete deck by #4 stirrups typically spaced at 9 in. Longitudinal reinforcement in the curb parapet was provided by two rows of two #5 and one row of three reinforcing bars. The interior posts were vertically reinforced with two #6 bars. The beam was longitudinally reinforced with five #4 reinforcing bars confined by #3 stirrups at the vertical post reinforcement locations. All occupant risk values were within MASH limits, and the barrier successfully contained and redirected the test vehicle according to MASH test designation no. 5-12 [29].

In test nos. 469689-2-1 and 469689-2-2, a transition section was crash tested to MASH test designation nos. 3-20 and 3-21 [41]. The transition was designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier, the TxDOT T221. The transition was vertically reinforced with #5 reinforcing stirrups spaced at 12 in. longitudinally. The concrete transition was longitudinally reinforced by five rows of two #5 reinforcing bars with the top row angled to match the slope of the transition section. The transition was anchored by 21-in. long #6 reinforcing bars embedded 6 in. into concrete pavement using Hilti HIT-RE 500 V3 epoxy and spaced longitudinally at 8 ft. The anchorage spacing was reduced to 2 ft for the last three anchorage bars at each end of the system outside of the transition area. In test nos. 469689-2-1 and 469689-2-2, all occupant risk values were within MASH limits, and the barrier transition successfully contained and redirected the test vehicles according to MASH test designation nos. 3-10 and 3-11 [41].

3 METHODOLOGY

3.1 Overview

Barriers submitted by the members of the Midwest Pooled Fund Program were evaluated to MASH 2016 TL-3 or TL-4 requirements, as appropriate. Requirements were applied to each barrier as presented in the flow diagram in Figure 15. If the TL-4 requirements were not met, the test level was reduced to TL-3, and the barrier was reevaluated to potentially justify crashworthiness under less restrictive standards. If a barrier system could not be justified as crashworthy at the reduced test level, the evaluation concluded, and the barrier was deemed "inconclusive" for TL-3. This "inconclusive" designation is an acknowledgement that future research or crash testing might yet justify barrier crashworthiness.

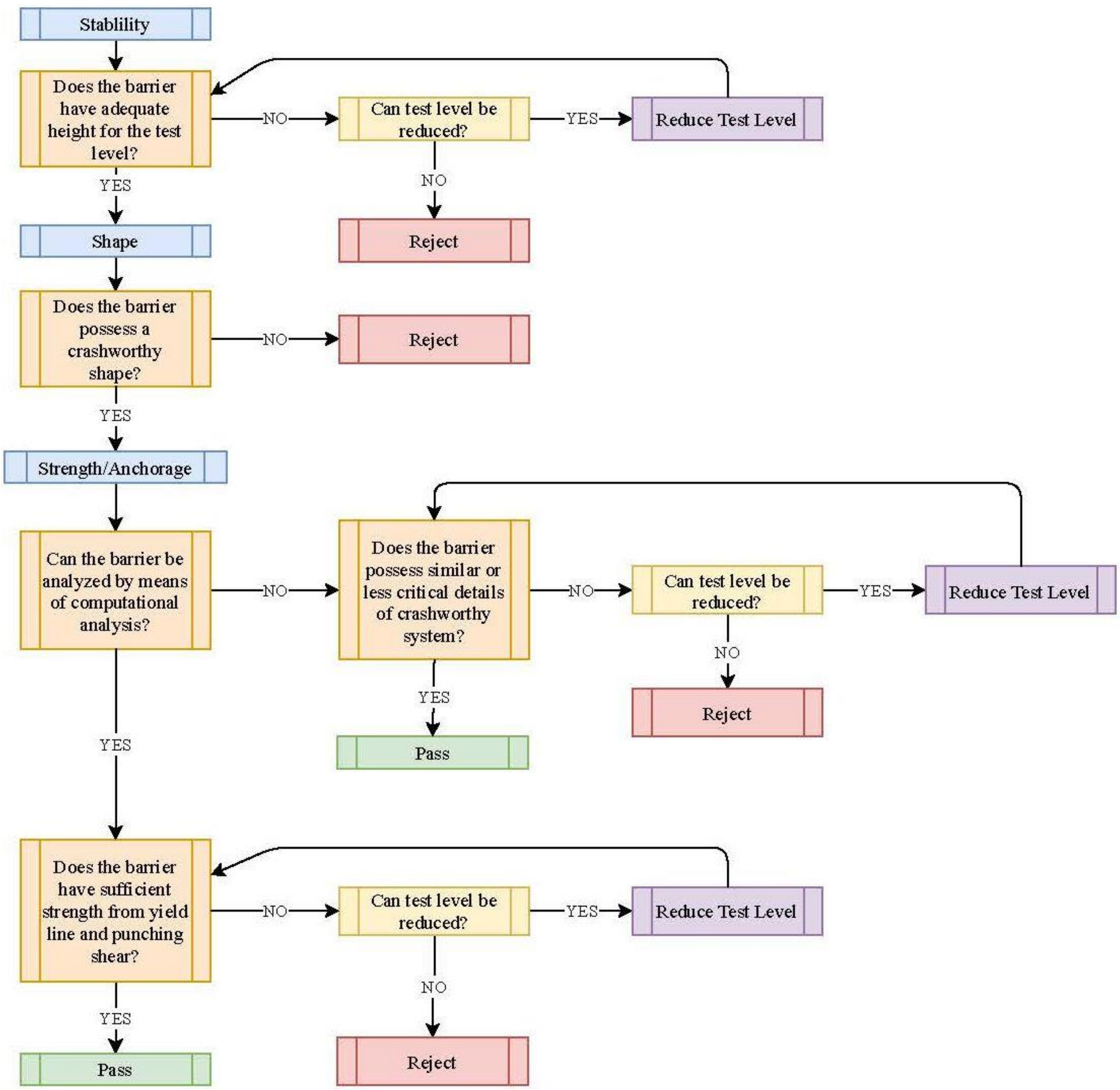

Figure 15. Evaluation Methodology

3.2 Stability

Increased TL-3 and TL-4 impact severities in MASH correspond to increased risk of vehicle rollover compared to NCHRP Report 350. Barrier height is a key factor in determining the propensity for vehicle rollover. Therefore, significant research has been performed using FE simulations in LS-DYNA to determine minimum barrier heights, and the limiting heights have largely been demonstrated to be adequate in full-scale MASH crash tests. In the barrier evaluations, if the barrier did not satisfy the TL-4 height requirement, the barrier was reevaluated at TL-3. If the barrier could not satisfy the stability requirement of TL-3, the barrier was deemed non-crashworthy for the purposes of the present study.

3.2.1 Test Level 3 Stability

NCHRP Project 20-07(395) researched the minimum height of MASH TL-3 barriers by conducting FE simulations in LS-DYNA [10]. The research verified the simulations by comparing gyro angles from a full-scale crash test to a corresponding simulation. Simulations were then performed on barriers with various heights, and a minimum height for MASH TL-3 barriers was found to be 29 in, which was a 2 in. increase to the 27 in. recommendation provided in the AASHTO LRFD Bridge Design Specifications for NCHRP Report 350 TL-3 barriers [7].

However, the shortest TL-3 barrier that has been successfully crash tested to MASH TL-3 is a 30 in. timber railing [42]. In addition, the greatest vehicle climb has been observed in New Jersey and F-shape barriers due to their traffic face geometry. New Jersey and F-shape barriers have only been successfully crash tested to MASH at heights of 32 in. or greater [24, 34, 37]. Therefore, to meet stability requirements for MASH TL-3 crashes, it is believed that all permanent concrete barriers must possess a minimum height of 32 in. for New Jersey and F-shape barriers and 30 in. for all other barriers.

3.2.2 Test Level 4 Stability

The minimum height of MASH TL-4 barriers was researched in FHWA/TX-12/9-1002-5 by conducting FE simulations and verifying the simulations with a crash test, test no. 420020-9b [11]. The simulations began at a 42-in. barrier height and gradually decreased the height to 36 in. At 36 in., the SUT test vehicle was at the edge of instability and any further height reduction would result in unacceptable risk of vehicle instabilities. Therefore, the parametric simulations ended, and 36 in. was declared the minimum acceptable rail height.

In the verification crash test on a 36-in. tall, single-slope barrier system, test no. 420020-9b, impact characteristics were similar to the FE simulations. Notably, the rear wheels of the test vehicle pitched upward near the top of the rail as the vehicle was redirected by the barrier. The crash test on the 36-in. tall barrier met all MASH test designation no. 4-12 evaluation criteria. TTI researchers acknowledged that without additional testing on a New Jersey or F-shape barrier, there may be disagreement in the roadside safety community over the minimum height due to vehicle climb associated with the New Jersey and F-shape profiles. However, previous MASH crash tests have not exhibited significant SUT climb due to toe interaction in safety shapes. Therefore, to meet stability requirements for MASH TL-4 crashes, all permanent concrete barriers must possess a minimum height of 36 in.

3.3 Shape

The primary concerns related to the overall geometry and traffic face shape of a barrier are propensities for vehicle climb and occupant compartment deformation. It has been observed that the greatest effects of these criteria occur in the passenger car and pickup truck tests, MASH test designation nos. 10 and 11. Therefore, traffic face shapes were evaluated based on crash testing performed according to the guidelines of these tests.

3.3.1 Vertical Barriers

Two MASH test designation no. 3-10 tests have been conducted on vertical barriers, test nos. 130MASHC13-02 and H42BR-1. In test no. 130MASHC13-02, a 32-in. tall vertical barrier was placed on top of an 8-in. tall elevated sidewalk [32]. Test no. H42BR-1 involved a 42-in. tall vertical barrier with minor recessed asperities [21]. Both systems satisfied all safety requirements of MASH tests designation no. 3-10.

The TxDOT T222 Bridge Rail was crash tested to MASH test designation no. 3-11 in test no. 490024-2-1. The vertical traffic face test article, designed for use in retrofit situations, adequately contained and redirected the pickup truck test vehicle according to MASH [43]. Additionally, a 42-in. tall vertical barrier was recently tested to MASH test designation no. 3-11 under test no. H42BR-2. The 2270P vehicle impacted the barrier and was successfully redirected according to all applicable evaluation criteria established in MASH [21]. Therefore, permanent concrete barriers with a vertical traffic face were assessed as crashworthy to MASH TL-3 and TL-4 provided all other evaluation criteria were met.

3.3.2 New Jersey Barriers

A New Jersey Safety Shape traffic face typically consists of a 3-in. tall toe, a 10-in. tall section at 35 degrees from vertical, and a 6-degree section extending to the top of the barrier, as shown in Figure 16. New Jersey sections possessing a height of 32-in. have been successfully crash tested to MASH test designation nos. 3-10 and 3-11 under test nos. 2214NJ-1 and 476460-1-4. New Jersey shape barriers have been observed to induce the greatest vehicle climb among all typical face profiles. As discussed in Section 3.2.1, crash testing of New Jersey barriers has only been successful for barriers 32 in. or taller, and 32 in. was established as the minimum New Jersey barrier height for stability at TL-3. Therefore, permanent concrete barriers with a New Jersey shape traffic face were assessed as crashworthy to MASH TL-3 and TL-4 provided all other evaluation criteria were met.

Figure 16. Typical New Jersey and F-Shape Traffic Face Geometry

3.3.3 F-Shape Barriers

As shown in Figure 16, the typical F-shape traffic face is similar to the New Jersey Safety Shape. The New Jersey shape's 10-in. high, 35-degree section is replaced with a 7-in. high, 35-degree section, and the transition between the 35-degree and 6-degree sections is filleted. Only one MASH crash test has been performed on a permanent F-shape barrier. A 32-in. tall barrier was tested to MASH test designation no. 3-11 under crash test no. 469467-5-1. The barrier adequately contained and redirected the 2270P test vehicle and satisfied all occupant risk criteria.

Unfortunately, a MASH test designation no. 3-10 crash test has not been performed on an F-shape barrier. Due to the limited crash test data, further justification for MASH crashworthiness was required. The F-shape is considered less critical than the New Jersey Shape because the 3-in. height reduction of the 35-degree section reduces vehicle climb. Furthermore, occupant risk is reduced compared to the vertical barrier shape because the contoured F-shape profile creates less impulse than a vertical barrier. Since both the New Jersey shape and vertical profiles are believed to satisfy the evaluation criteria of MASH, so too is the F-shape. Therefore, permanent concrete barriers with an F-shape traffic face were assessed as crashworthy to MASH TL-3 and TL-4 provided all other evaluation criteria were met.

3.3.4 Single-Slope Barriers

Single-slope barriers have been successfully crash tested to MASH test designation nos. 3-10 and 3-11 one and three times, respectively, in test nos. 140MASH3C16-04, OSSB-1, 420020-3, and 405160-13-1. The shallowest face angle tested was 11 degrees in test no. 420020-3 in which the 2270P test vehicle was successfully contained and redirected. Although an 11-degree single-slope barrier has not been tested under MASH test designation no. 3-10, it is believed to be crashworthy to MASH test designation no. 3-10 based on observations for successfully crash tested New Jersey and Vertical shape barriers (see Sections 3.3.1 and 3.3.2). New Jersey Shapes have been observed to cause the greatest vehicle climb of all the typical traffic face shapes. Additionally, the greatest occupant compartment deformations have been observed in vertical barriers due to the increased impulse induced by the vertical traffic face. Therefore, since successful MASH test designation no. 3-10 crash tests have been performed on New Jersey and Vertical barriers, it is believed that 11-degree and steeper single-slope barriers would possess crashworthy traffic-face profiles. Note, shallower face slopes may be acceptable to MASH, but as the profile becomes shallower there may be an increased risk of vehicle climb up the barrier. Therefore, barriers with a face slope shallower than 11-degrees could not be justified to MASH TL-3 or TL-4.

Therefore, permanent concrete barriers with a single-slope traffic-face profile were assessed as crashworthy to MASH TL-3 and TL-4 provided all other evaluation criteria were met.

3.4 Strength and Anchorage

Permanent concrete barrier systems must provide adequate strength and anchorage to adequately contain and redirect vehicles. Failure to provide sufficient strength and anchorage could result in a vehicle passing through a barrier, resulting to increased risk to other motorists on the roadway, or in unpredictable vehicle dynamics posing unacceptable risk to the impacting vehicle's occupants or other traffic. Strength and anchorage limit states that could be computationally analyzed included yield line, punching shear, and geotechnical analyses.

3.4.1 Computational Analysis of Strength

Where applicable, barrier strength was calculated according to yield line theory as recommended in Section 13 of the AASHTO LRFD Bridge Design Specifications [7]. In addition, barriers were analyzed for resistance to punching shear as described within Section 5 of the AASHTO LRFD Bridge Design Specifications [7]. Where computational analysis was deemed insufficient or did not provide conclusive results, the barrier was then compared to crash tests in the database to determine if it had similar details to a successful crash test that could be used to justify its crashworthiness to MASH TL-3 or TL-4.

3.4.1.1 Yield Line Analysis of Solid Concrete Barriers

Significant research has been directed towards quantifying updated design forces and identifying effective heights for TL-3 and TL-4 impacts on concrete barriers [8–10]. Using the information gathered in those research efforts, criteria were developed to computationally analyze the strength of the concrete barriers. The researchers determined that the impact force increases as the height of the barrier is increased. The developed strength criteria reflected this observation and led to the recommendation of design impact forces shown in Table 11 [8–10]. Table 11 includes the effective height of the impact force above the driving surface.

Table 11. Computational Strength Analysis Criteria, [8–11]

Test Level	Barrier Height, H in.	Impact Force, F_t kips	Effective Height, H_e in.
TL-3	≥30	70	24
TL-4	36	70	25
	>36	80	30

The AASHTO LRFD Bridge Design Specifications [7] give Equations 3 and 4 below, to evaluate the strength of concrete barriers via yield line analysis. These equations were derived in accordance with Figures 17 and 18 for impacts within a wall segment and near the end section of a wall segment.

Yield line analysis is performed through the equilibrium of the internal and external work done to the system. The variables required to perform this analysis are the longitudinal distribution of the impact force in ft (L_t), the longitudinal critical length in ft (L_c), the total wall and beam flexural strength about a vertical axis in kip-ft (M_b and M_w), the cantilever flexural strength per ft about a horizontal axis in kip-ft/ft (M_c), and the height of the barrier in ft (H). The longitudinal critical length can be determined from Section 13 of the AASHTO LRFD Bridge Design Specifications [7].

For impacts away from ends of wall segments [7]:

$$R_w = \left(\frac{2}{2L_c - L_t}\right)\left(8M_b + 8M_w + \frac{M_c {L_c}^2}{H}\right) \tag{3}$$

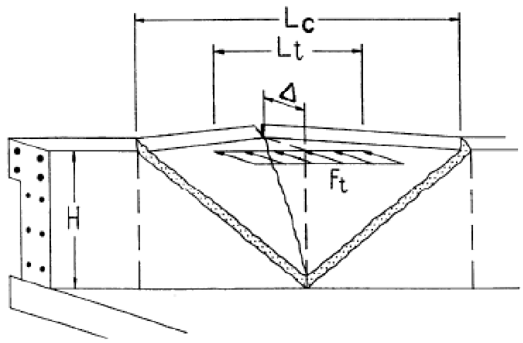

Figure 17. Yield Line Analysis of Impacts Away from Ends of Wall Segments [7]

For impacts at ends of wall segments (including discontinuous joints) [7]:

$$R_w = \left(\frac{2}{2L_c - L_t}\right)\left(M_b + M_w + \frac{M_c {L_c}^2}{H}\right) \tag{4}$$

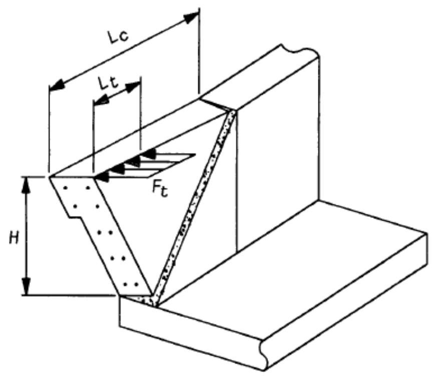

Figure 18. Yield Line Analysis of Impacts near Ends of Wall Segments [7]

The strength equations provided by AASHTO assume the load is applied along the top edge of the barrier. Yield line analyses can be modified to remove unnecessary conservativism by deriving the strength based on the effective height in ft (H_e) of the transverse force as given in Table 11. The derivation yields Equations 5 and 6, which were used in all subsequent yield line calculations. Barriers possessing a maximum impact force resistance in kips (R_w) greater than the design impact forces in kips (F_t) listed in Table 11 were assessed as crashworthy to the applicable MASH test level provided all other criteria were met.

For impacts within wall segment:

$$R_w = \left(\frac{H}{H_e}\right)\left(\frac{2}{2L_c - L_t}\right)\left(8M_b + 8M_w + \frac{M_c {L_c}^2}{H}\right) \tag{5}$$

For impacts at end of wall or at joint:

$$R_w = \left(\frac{H}{H_e}\right)\left(\frac{2}{2L_c - L_t}\right)\left(M_b + M_w + \frac{M_c {L_c}^2}{H}\right) \tag{6}$$

3.4.1.2 AASHTO Punching Shear Analysis of Permanent Concrete Barriers

In addition to yield line strength, barriers were also analyzed for strength against punching shear failure. Calculations for punching shear strength were performed according to the requirements of Section 5 of the AASHTO LRFD Bridge Design Specifications [7]. The nominal punching shear resistance of concrete (V_n) according to Equation 7 is calculated using the concrete compressive strength (f'_c), concrete density modification factor (λ), critical perimeter (b_o), and the transverse depth of the barrier (d_f). AASHTO also provides provisions for reducing the two-way shear strength of a section according to the ratio of the dimensions of the loaded section. However, this methodology was not utilized in the barrier evaluations since the distribution of the impact load as it pertains to punching shear is idealized as an evenly distributed line load acting at the effective height of the barrier.

$$V_n = 0.125\lambda\sqrt{f_c'}b_o d_f \tag{7}$$

In most barriers, the transverse depth varies over the barrier height. To idealize Equation 7 for barrier applications, the transverse depth (d_f) in the punching shear equation was split into separate depths as shown in to Figure 19. The critical perimeter was calculated by determining the lengths of the failure plane as shown in Figures 20 and 21 for interior and end sections, respectively. Additionally, due to the varying transverse depth, the top width (d') of the barrier was conservatively used as the depth to develop the bottom thickness dimensions of the critical perimeter (d_{bot}). The barrier thickness at the effective height (d_t) was also determined in this manner. The height of the barrier (H), the effective height of the impact (H_e), and the longitudinal distribution of the impact force (L_t) are consistent with the same variables used in the yield line analysis. Using these geometric idealizations and substituting them into the general punching shear equation resulted in Equations 8 and 9 for the two-way concrete shear strength at interior and end sections. Equations 8 and 9 were used to determine the nominal punching shear strength in kips of the barrier (V_n). Note, Figures 19 through 21 are shown for single-slope and vertical barrier profiles, but the equations are applicable to other barrier types. All variables in equations 8 and 9 use units of kips and inches, and punching shear strength is calculated in units of ksi.

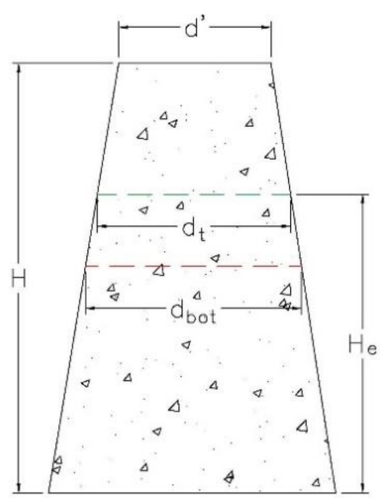

Figure 19. Punching Shear Cross Section [7]

For impacts within wall segment:

$$V_n = 0.125\lambda\sqrt{f_c'}\left[d_{bot}(L_t + d') + (d_{bot} + d')\left(H - H_e + \frac{d_t}{2}\right)\right] \tag{8}$$

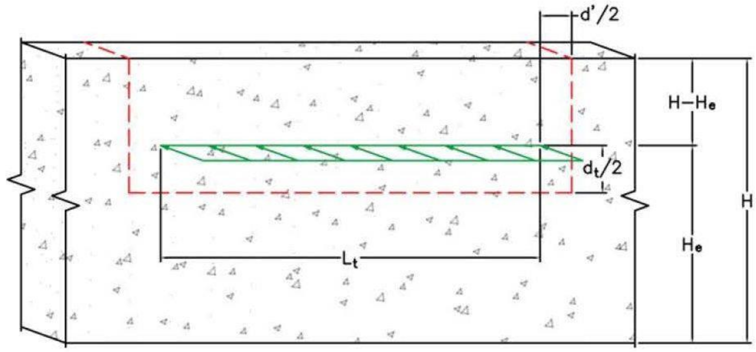

Figure 20. Punching Shear at Interior Sections [7]

For impacts at end of wall or at joint:

$$V_n = 0.125\lambda\sqrt{f_c'}\left[d_{bot}(L_t + d') + \frac{1}{2}(d_{bot} + d')\left(H - H_e + \frac{d_t}{2}\right)\right] \tag{9}$$

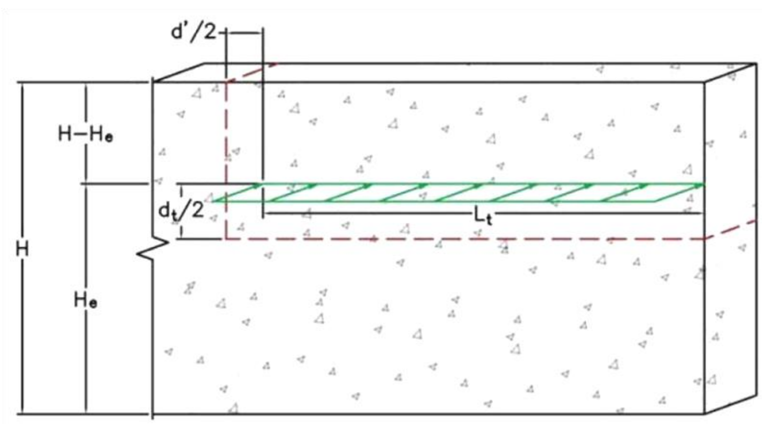

Figure 21. Punching Shear at End Sections [7]

Not all permanent concrete barriers include transverse reinforcing, and therefore only concrete resistance was considered. AASHTO 5.5.4.2 specifies a resistance factor (ϕ) of 0.9 for shear limit states and the factored punching resistance is given by Equation 10. The factored resistance must be greater than the design impact load (F_t) determined by NCHRP Project 22-20(02) for the respective MASH test level, as summarized in Table 11.

$$\phi V_n = 0.9V_n \tag{10}$$

3.4.2 Computational Analysis of Anchorage

Barriers properly anchored to a sizable concrete slab or deck with rebar ties or dowel bars can be evaluated using yield line analysis. In instances where the anchorage details could not be evaluated by traditional yield line analysis, further investigation was required. Common scenarios requiring additional analysis included barriers with moment slabs and footings. Static design guidelines for moment slabs above MSE walls have been proposed within in NCHRP Project 22(20)-02 [8]. These design guidelines were utilized, and the methodology modified to apply to other types of structurally independent foundations.

A variety of rebar anchorage systems have been crash tested to MASH test designation nos. 3-11 and 4-12, which are believed to produce the maximum anchorage stresses for TL-3 and TL-4 crashes, respectively. Typical tested anchorage systems found in the literature review included: stirrups of varying shape, size, and spacing; continuation of vertical reinforcement; retrofit epoxied rebar; and through-deck bolted connections. Where vertical reinforcement was provided in tandem with rebar anchorage to a concrete deck or slab, the anchorage was computationally analyzed as part of the yield line analysis for strength as documented in Section 3.4.1.

Yield line theory in concrete slabs, or barriers, requires reinforcing in two directions to provide plastic moment capacity along yield lines. The plastic moments provide internal work to balance against external work from applied loads. Therefore, systems with rebar anchorages only at the base and lacking vertical reinforcement continuing along the height of the barrier could not be analyzed using typical yield line theory. These barrier systems were only assessed by direct comparison to database crash tests.

3.4.3 Direct Comparison of Strength and Anchorage

Where conventional yield line analysis and punching shear calculations could not be determined due to the anchorage or reinforcement details, a direct comparison of section dimensions and reinforcement details was performed between the barrier under evaluation and MASH crashworthy systems or applicable FE simulations. The barriers were compared to systems in the crash testing database and FE simulations from the literature review. If a barrier had the similar details to current MASH crashworthy barriers, the barrier was then justified as possessing the necessary strength to withstand impacts at the test level of the MASH crashworthy barrier. A list of applicable MASH crash tests on permanent concrete barriers is provided in Table 12, with the cause of test failure bolded in the MASH Result column.

Table 12. MASH Crash Tests for Direct Comparison

Test No.	MASH Test Level	Test Designation No.	Profile	Height in.	MASH Result
OSSB-1 [22]	TL-3	11	Single-slope	42	Pass
2214NJ-1 [34]	TL-3	10	NJ	32	Pass
2214NJ-2 [35]	TL-4	12	NJ	32	**Rollover**
140MASH3C16-04 [23]	TL-3	10	Single-slope	36	Pass
130MASH3C13-02 [32]	TL-3	10	Vertical	32	**Ridedown Accel.**
130MASH3P13-01 [32]	TL-3	11	Vertical	32	Pass
110MASH2C14-01 [32]	TL-2	10	Vertical	32	Pass
420020-9b [11]	TL-4	12	Single-slope	36	Pass
469467-1-1 [24]	TL-4	12	Vertical	36	Pass
469467-3-1 [24]	TL-4	12	Single-slope	42	Pass
469467-5-1 [24]	TL-3	11	F-shape	32	Pass
401761-SBG1 [36]	TL-5	12	NJ	42	Pass
490027-2-1 [26]	TL-4	12	Single-slope	42	Pass
MAN-1 [27]	TL-5	12	Single-slope	49¼	Pass
420021-5 [40]	TL-3	11	Post-and-Beam	32	Pass
420020-3 [11]	TL-3	11	Single-slope	36	Pass
490024-2-1 [33]	TL-3	11	Vertical	32¾	Pass
490025-2-2 [38]	TL-5	10	Post-and-Beam	42	Pass
490025-2-3 [38]	TL-5	11	Post-and-Beam	42	Pass
490025-2-1 [38]	TL-5	12	Post-and-Beam	42	Pass
476460-1b [37]	TL-4	12	NJ	32	**Overrode/Rollover**
476460-1-4 [37]	TL-3	11	NJ	32	Pass
475350-1 [14]	TL-3	11	Vertical	32	Pass
607451-1 [39]	TL-4	12	Combination	44	Pass
607451-2 [39]	TL-4	11	Combination	44	Pass
607451-3 [39]	TL-4	10	Combination	44	Pass
469468-2-1 [29]	TL-5	12	Combination	42	Pass
469468-6-1 [29]	TL-4	12	Single-slope	42	Pass
405160-13-1 [30]	TL-3	11	Single-slope	32	Pass
4CBR-1 [31]	TL-4	12	Single-slope	36	Pass
510602-EWP1 [15]	TL-4	12	Single-slope	36	Pass
H34BR-1 [20]	TL-3	10	Aesthetic	34	Pass
H34BR-2 [20]	TL-3	11	Aesthetic	34	Pass
469689-3-3 [12]	TL-4	12	Single-slope	36	Pass
610221-01-1 [25]	TL-4	12	Single-slope	41	Pass
469689-2-1 [41]	TL-3	20	Transition	37 [(a)]	Pass
469689-2-2 [41]	TL-3	21	Transition	37 [(a)]	Pass
H42BR-1 [21]	TL-3	10	Aesthetic	42	Pass
H42BR-2 [21]	TL-3	11	Aesthetic	42	Pass

(a) Average height of transition section.

3.4.3.1 Asphalt Keyways

Two barrier systems with asphalt keyway anchorages have been MASH crash tested, one TL-3 and one TL-4 system. Both systems performed acceptably to the evaluation criteria outlined in MASH. However, the mechanical interaction of keyways with barriers is not clearly understood. It is believed that much of the impact resistance comes less from the keyway than from the overturning stability and large mass of the total barrier sections. Due to simple statics, the overturning stability of the barrier can be significantly affected by the base width of the cross section, and the mass can be taken as a function of the unjointed length and the dimensions of the cross section.

In test no. OSSB-1 [22] a single-slope barrier with a 1-in. deep asphalt keyway anchorage system met all evaluation criteria outlined in MASH for test designation no. 3-11. In test no. 469467-3-1 [24] a single-slope barrier with a 1-in. deep asphalt keyway anchorage system met all evaluation criteria outlined in MASH for test designation no. 4-12. Details of the crash tested barriers are summarized in Table 13.

Table 13. Asphalt Keyway Parameters of MASH Crash Tested Barriers

Evaluation Parameter	OSSB-1 (TL-3) [22]	469467-3-1 (TL-4) [24]
Keyway Depth	1 in.	1 in.
Keyway Width	8 ft	9 ft
Base Width	28⅜ in.	24 in.
Top Width	12 in.	8 in.
Height	43 in.	42 in.
Longitudinal Reinforcement	Unreinforced	14 x D18 WWR
Vertical Reinforcement	Unreinforced	D9 WWR
Section Weight	904 plf	700 plf
Overturning Stability	1,070 ft-lb/ft	700 ft-lb/ft
Static Overturning Demand	140 kip-ft	200 kip-ft

The section weight as displayed in Table 13 was determined by calculating the cross-sectional area of the barrier (A_c) and multiplying by the density of concrete, taken as 145 lb/ft^3, as shown in Equation 11.

$$Section\ Weight = A_c \times 145\ \frac{lb.}{ft^3} \tag{11}$$

The overturning stability per foot of barrier length, as displayed in Table 13, was determined by calculating the static overturning moment of the barrier section, assuming no anchorage, and rotation around the base where it meets the non-traffic face. It was calculated according to Equation 12 where the moment arm is taken as the horizontal distance between the center of gravity of the barrier and the point of assumed rotation (y_c).

$$Overturning\ Stability = Section\ Weight\ \times y_c \tag{12}$$

The overturning demand as displayed in Table 13 was determined by calculating the moment produced by design impact forces (F_t) acting at the effective height (H_e) from Table 11 for the highest MASH Test Level to which the barrier could be evaluated due to height requirements. This process was executed according to Equation 13.

$$Overturning\ Demand = F_t \times H_e \tag{13}$$

A static assessment would predict unstable performance and barrier rotation during a crash event. However, the short duration pulse from an impacting vehicle resulted in adequate performance for each of the barriers in full-scale tests. Based on the limited amount of crash testing available and the lack of current analysis methods, the dimensions presented in Table 13 were used when evaluating the crashworthiness of permanent concrete barrier systems. In order to be considered for MASH crashworthiness a barrier must have similar or less critical details and dimensions to those presented in Table 13.

3.4.3.2 Moment Slab Anchorage

Direct comparisons for moment slabs were based on FE simulations [12] and crash testing performed in test nos. 475350-1 [14], 510602-EWP1 [15] and 469689-3-3 [12]. Applicable dimensions of the barriers and moment slabs of these systems are displayed in Table 14.

Table 14. MASH Crashworthy Moment Slab Systems

Test Level	Test Type	Barrier Height	Width	Thickness	Segment Length	Average Cover	Soil Restraint	Wall Coping	Notes	Reference
TL-4	FE	36 in.	36 in.	8 in.	50 ft	None	8 in.	N	N/A	[12]
TL-4	FE/ CT	36 in.	60 in.	12 in.	20 ft	None	12 in.	N	N/A	[12]
TL-4	CT	36 in.	96 in.	18 in.	8 ft	30 in.	N/A	N	a, b	[15]
TL-3	CT	32 in.	48 in.	15 in.	30 ft – 1 in.	9 in.	N/A	Y	a, c	[14]

N/A – Not Applicable, FE – Finite Element Analysis, CT – Crash Test
(a) Rested on Mechanically Stabilized Earth (MSE) wall.
(b) GRAVIX® Barrier details small trapezoidal (9½ in. and 39 in.) moment slab with keys abutting MSE Wall
(c) Width measured from traffic face of coping section.

For a barrier moment slab system to be crashworthy to MASH 2016 by direct comparison, it must have similar or less critical details to the simulations and crash tests presented in Table 14. Additionally, crashworthy evaluations must have met all other evaluation criteria documented herein.

3.4.3.3 Footings

The direct comparison of footing anchorages was based on FE simulations [12] and a single crash test, 401560-13-1 [30]. The footing systems in these simulations and crash testing have been shown crashworthy to MASH and are documented with dimensions in Table 15.

Table 15. MASH Crashworthy Stand-Alone Footings

Test Level	Test	Barrier Height	Base Width	Depth	Segment Length	Ditch Slope	Ditch Offset	Reference
TL-4	FE-1	36 in.	16 in.	33 in.	30 ft	1V:2H	1 ft	[12]
TL-4	FE-2	36 in.	18 in.	27 in.	50 ft	N/A	N/A	[12]
TL-4	FE-3	36 in.	13 in.	10 in.	50 ft	N/A	N/A	[12]
TL-3	CT	32 in.	*24 in.	10 in.	20 ft	1.5V:2H	2 ft	[30]

N/A – Not Applicable, FE – Finite Element Analysis, CT – Crash Test
*Foundation is battered to match slope of barrier.

For a barrier footing system to be crashworthy to MASH by direct comparison it must have similar or less critical details to the simulations and crash tests presented in Table 15. Additionally, crashworthy evaluations must have met all other applicable evaluation criteria.

3.4.3.4 Combination Anchorages

Combination anchorages feature two or more anchorage types. Analysis methods for these anchorages have yet to be developed and thus could only be deemed MASH crashworthy if a similar crash test had already been conducted or if one of the anchorages provided enough resistance by itself as evidenced by crash testing or computational analysis.

3.4.3.5 Dowel and Reinforcing Bar Anchorage and No Vertical Reinforcement

As previously mentioned, dowel bars and rebar anchorage may be analyzed through yield line theory when accompanied by vertical reinforcement and anchored within a significant concrete slab or bridge deck. When a barrier used a dowel bar or rebar anchorage without vertical barrier reinforcement, direct comparison was the only option to determine crashworthiness to MASH. Unfortunately, only a single MASH crash test has been performed on a barrier featuring only longitudinal reinforcement, test no. 140MASH3C16-04 [23]. In test no. 140MASH3C16-04, a 1100C passenger car test vehicle was successfully crash tested to MASH test designation no. 3-10. The barrier was anchored at its ends by a monolithic 24-in. wide by 10-in. deep by 10-ft footing. No interior anchorage or interior vertical reinforcement was provided, and the barrier was longitudinally reinforced by four rows of two #5 reinforcing bars.

The lack of vertical reinforcement and interior anchorage in this testing provides some evidence that barriers containing minimal or no anchorage and vertical reinforcement may be crashworthy to MASH. However, the testing was only performed at MASH test designation no. 3-10, the lowest impact severity of the tests in this study. For further implementation to occur with these reinforcement and anchorage details, more critical crash testing would be required. No crash testing of such barriers yet exists, and therefore barriers lacking vertical reinforcement with these anchorages could not be justified to MASH 2016.

3.5 Summary of Evaluation Criteria

3.5.1 Stability Evaluation Criteria

Stability evaluations were performed by comparing the barrier height to the requirements in Table 16.

Table 16. Stability Evaluation Criteria

MASH Test Level	Barrier Type	Height
TL-3	Single-Slope Vertical Other	≥30 in.
	New Jersey F-Shape	≥32 in.
TL-4	All Types	≥36 in.

3.5.2 Shape Evaluation Criteria

The shape evaluation criteria were strictly based on previous crash testing as discussed in Section 3.3. Barriers featuring a Single-slope, Vertical, New Jersey, or F-shape traffic face were deemed crashworthy if they had met the applicable stability requirement. These four traffic face profiles were typical of the barriers submitted. Other barrier traffic face shapes were considered on an individual basis.

3.5.3 Strength and Anchorage Evaluation Criteria

When possible, strength and anchorage were first assessed utilizing the computational methods described in Section 3.4 and the calculated capacities were compared to the design impact forces shown Table 17. To satisfy strength and anchorage criteria by computational methods, the minimum calculated yield line and punching shear strengths at interior and end sections must be greater than the design impact force for the applicable MASH test level. If a computational assessment was not possible or the results were inconclusive, the direct comparison methods described in Section 3.4 were employed.

Table 17. Strength and Anchorage Evaluation Criteria, [8–11]

MASH Test Level	Barrier Height, H	Impact Force, F_t
TL-3	≥30 in.	70 kips
TL-4	36 in.	70 kips
	>36 in.	80 kips

4 SUMMARY OF BARRIER EVALUATIONS

Permanent concrete barrier details were submitted for evaluation by the member states of the Midwest Pooled Fund Program, and 51 of the submitted systems were selected for evaluation. Several systems included alternate details, most commonly for the anchorage configuration. Taking these alternatives into account, a grand total of 85 permanent concrete barrier variations were evaluated.

4.1 Characteristics of Barriers Selected for Evaluation

The barrier details most relevant to the MASH evaluations were height, traffic face shape, the presence of longitudinal and vertical reinforcement at interior and end sections, and anchorage configuration. Of the 51 barrier systems, the minimum height was 32 in. and the maximum height was 57 in. The most common traffic face shape was the single-slope shape—32 barriers had single-slope traffic face geometry. There was also some apparent correlation between barrier height and profile. Of the 34 barriers that were 36 in. or taller, 29 (85%) had a single-slope traffic face, and at the other end of the height spectrum, there were no New Jersey barriers taller than 34 in. The heights and traffic face shapes of the 51 evaluated barrier systems are shown in Figures 22 and 23.

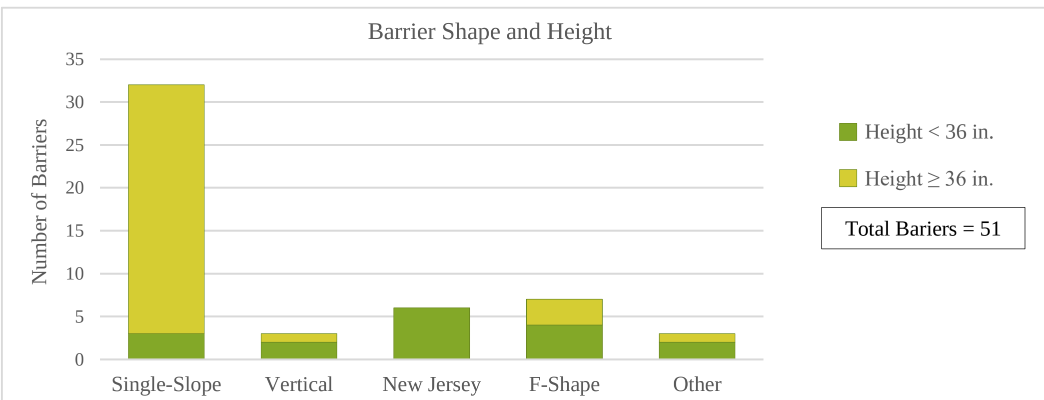

Figure 22. Height and Shape Characteristics for the Evaluated Barriers

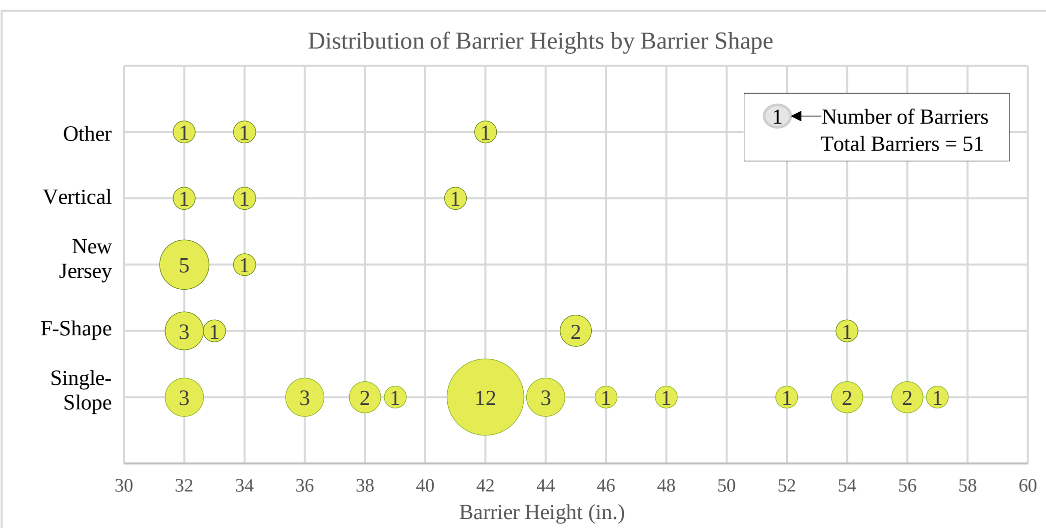

Figure 23. Distribution of Barrier Heights by Barrier Shape

Barrier reinforcement detailing was significant because yield line theory is only applicable when both longitudinal and vertical reinforcement are present. Without calculated yield line strengths at both interior and end sections, computational methods were inconclusive, and the barrier could only be evaluated by direct comparison. Comparison was challenging for many of these barriers because there were only two known crash tests on barriers without vertical reinforcement. As seen in Figure 24, five of the 51 barriers were entirely unreinforced and an additional 14 had no vertical reinforcement or vertical reinforcement only at end sections.

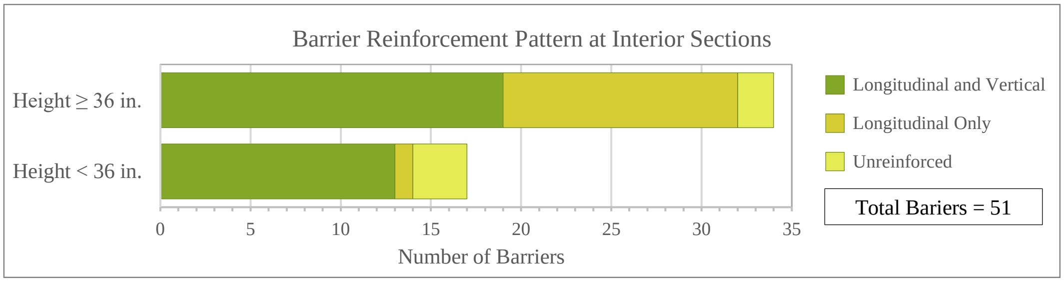

Figure 24. Reinforcement Details for the Evaluated Barriers

The final essential barrier parameter was the anchorage configuration. Computational evaluation could only be performed for variations where (1) the barrier included longitudinal and vertical reinforcement and (2) the anchorage consisted of adequately developed reinforcing bars of dowels. Of the 85 barrier variations, just 25 met these criteria. Many of the remaining variations were anchored by dowel bars, keyways, or footings, and the strength evaluation depended on direct comparison, often with a very limited number of MASH crash tests or FE simulations. The anchorage configurations used in the 85 barrier variations are shown in Figure 25.

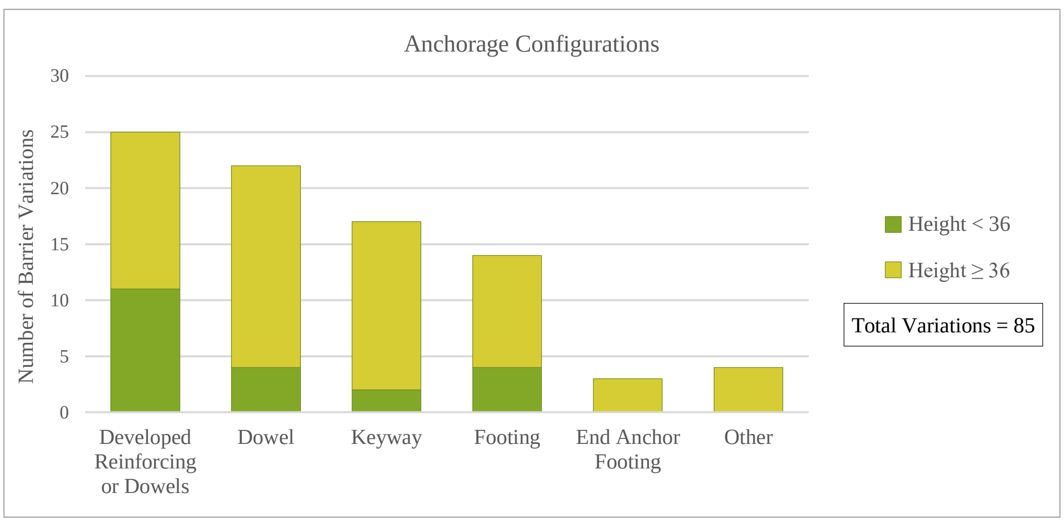

Figure 25. Anchorage Configurations for the Evaluated Barrier Variations

4.2 Evaluation Results

Barrier evaluations were conducted to MASH TL-3 and TL-4 for 85 permanent concrete barrier variations. A total of 22 variations were assessed as crashworthy to MASH TL-4 and an additional 42 variations were assessed as crashworthy to MASH TL-3. Figure 26 summarizes the overall evaluation results. Table 18 shows more detailed information for each barrier variation, including the individual stability, strength, and anchorage evaluations, as well as the overall TL-3 and TL-4 crashworthiness assessment. Further discussion for each barrier can be found in the appendices. The "Pass", "Inconclusive", and "Fail" evaluations were defined as follows:

Pass The barrier was evaluated as meeting MASH criteria for the test level.

Inconclusive *For strength and anchorage evaluations:* "inconclusive" indicates that barrier crashworthiness could not be justified by computation or direct comparison. In some cases, it is possible the barrier has adequate strength for a given test level, and future research or crash testing could provide the necessary justifications for MASH crashworthiness.

For stability evaluations at TL-4: 34-in. tall barriers were designated "inconclusive". Full-scale TL-4 crash testing has not yet been successful at this height, but in one FE simulation a 34.5-in. tall barrier contained and redirected the 10000S vehicle [44]. Future research and crash testing may demonstrate that 34-in. tall barriers are adequate for TL-4 stability.

Fail Barriers shorter than 34 in. were assessed as failing the TL-4 stability criterion. This was the only situation assigned a failing evaluation, and these barriers were not evaluated any further at TL-4.

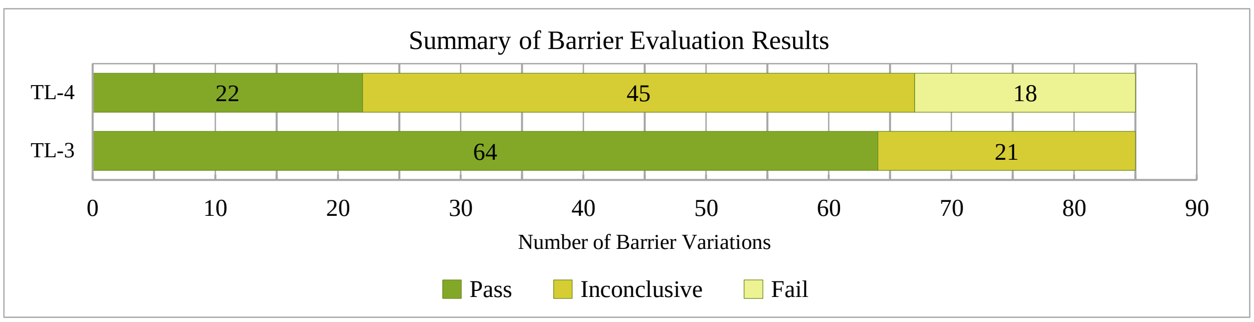

Figure 26. Summary of Barrier Evaluations

Table 18. Barrier Evaluation Results

State	Barrier	Anchorage	Ht in.	Shape	TL-3 Evaluation				TL-4 Evaluation			
					Ht	Str	Anch	Overall	Ht	Str	Anch	Overall
CA	732	Reinforcement	32	SS	P	P	P	Pass	F	-	-	Fail
	Type 732B	Footing	32	SS	P	P	P*	Pass	F	-	-	Fail
	Type 732SW	Reinforcement	41	V	P	P	P	Pass	P	P	P	Pass
FL	38-in. Curb and Gutter	Footing	38	SS	P	P	P*	Pass	P	P	P*	Pass
	38-in. Shoulder	Footing	38	SS	P	P	P*	Pass	P	P	P*	Pass
	44-in. Shoulder	Typical Footing	44	SS	P	P	P*	Pass	P	P	P*	Pass
		Front-Flush Footing					P*	Pass			P*	Pass
		Rear-Flush Footing					P*	Pass			P*	Pass
GA	Type 2-S	RC Retaining Wall	42	SS	P	P	I	Inconclusive	P	P	I	Inconclusive
	Type 3-SA/SB	RC Retaining Wall	42	SS	P	P	I	Inconclusive	P	P	I	Inconclusive
IL	Double Face Median	PCC Base w/ 2-in. Keyway	44	SS	P	P*	I	Inconclusive	P	I	I	Inconclusive
		8-in. Concrete Keyway					P*	Pass			I	Inconclusive
		10-in. Earthen Keyway					P*	Pass			I	Inconclusive
		1½-in. Asphalt Keyway					P*	Pass			I	Inconclusive
		Staggered #6 Dowel Bars					P*	Pass			I	Inconclusive
		#6 Dowels w/ Bond Breaker					I	Inconclusive			I	Inconclusive
	39-in. Parapet	Reinforcement	39	SS	P	P	P	Pass	P	P	P	Pass
	44-in. Parapet	Reinforcement	44	SS	P	P	P	Pass	P	P	P	Pass
IN	Type FC	Reinforcement	33	F	P	P	P	Pass	F	-	-	Fail
	Type FT	Reinforcement	45	F	P	P	P	Pass	P	P	P	Pass
	Concrete Median	Dowel Bars	45	F	P	P*	P*	Pass	P	I	I	Inconclusive
IA	Roadside Barrier	Reinforcement	54	F	P	P	P	Pass	P	P	P	Pass
	Vertical Bridge Rail	Reinforcement	34	V	P	P	P	Pass	I	-	-	Inconclusive
KS	Type II	Reinforcement	32	F	P	I	I	Inconclusive	F	-	-	Fail
	Type V	Reinforcement	32	V	P	P	P	Pass	F	-	-	Fail
MN	Type 36A	Doweled Footing	36	SS	P	P*	P*	Pass	P	I	I	Inconclusive
	Type 42A	Doweled Footing	42	SS	P	P*	P*	Pass	P	I	I	Inconclusive
	Type 54A	Doweled Footing	54	SS	P	P*	P*	Pass	P	I	I	Inconclusive

Ht = Height, Str = Strength, Anch = Anchorage
P = Pass, I = Inconclusive, F = Fail
* = Individual criterion justified based on crash tests or FE analyses

Table 19. Barrier Evaluation Results, Cont.

State	Barrier	Anchorage	Ht in.	Shape	TL-3 Evaluation				TL-4 Evaluation			
					Ht	Str	Anch	Overall	Ht	Str	Anch	Overall
MO	Type C	1-in. Dowel Bars	42	SS	P	P*	P*	Pass	P	I	I	Inconclusive
		1 3/4-in. Asphalt Keyway					P*	Pass			I	Inconclusive
		#8 Epoxy Rebar					P	Pass			I	Inconclusive
NE	34-in. Median Barrier	Reinforcement	34	O	P	P	P	Pass	I	-	-	Inconclusive
	42-in. Median Barrier	Reinforcement	42	O	P	P	P	Pass	P	P	P	Pass
NJ	Barrier Curb	Reinforcement	34	NJ	P	P	P	Pass	I	-	-	Inconclusive
	Concrete Median	Reinforcement	32	NJ	P	I	I	Inconclusive	F	-	-	Fail
	Split Median	Reinforcement	32	NJ	P	I	I	Inconclusive	F	-	-	Fail
	Barrier Curb	#8 Dowel with Pavement	32	NJ	P	I	I	Inconclusive	F	-	-	Fail
		#8 Dowel with Footing					I	Inconclusive			-	Fail
NC	Type I	2-in. Asphalt Keyway	32	NJ	P	P	P*	Pass	F	-	-	Fail
	Type IV	2-in. Asphalt Keyway	32	NJ	P	I	I	Inconclusive	F	-	-	Fail
	Single-Slope	1-in. Asphalt Keyway	42	SS	P	P	P*	Pass	P	P	P*	Pass
	Single-Slope	1-in. Asphalt Keyway	48	SS	P	P	P*	Pass	P	P	P*	Pass
	Single-Slope	1-in. Asphalt Keyway	52	SS	P	P	P*	Pass	P	P	P*	Pass
OH	Type B	1-in. Asphalt Keyway	42	SS	P	P*	P*	Pass	P	I	I	Inconclusive
		4-in. Concrete Keyway					P*	Pass			I	Inconclusive
		Staggered #8 Dowel Bars					P*	Pass			I	Inconclusive
	Type B1	1-in. Asphalt Keyway	57	SS	P	P*	P*	Pass	P	I	I	Inconclusive
		4-in. Concrete Keyway					P*	Pass			I	Inconclusive
		Staggered #8 Dowel Bars					P*	Pass			I	Inconclusive
	Type D	1-in. Asphalt Keyway	42	SS	P	I	I	Inconclusive	P	I	I	Inconclusive
		Staggered #8 Dowel Bars					P*	Inconclusive			I	Inconclusive
SC	Type 36SS	4-in. Pavement Keyway	36	SS	P	P	P*	Pass	P	P	P*	Pass
		End Anchor Footing					I	Inconclusive			I	Inconclusive
		Continuous Footing					P*	Pass			P*	Pass
		Cast-In or Epoxied Bars					P	Pass			I	Inconclusive
	Type 46SS	4-in. Pavement Keyway	46	SS	P	P	P*	Pass	P	P	P*	Pass
		End Anchor Footing					I	Inconclusive			I	Inconclusive
		Continuous Footing					P*	Pass			P*	Pass
		Cast-In or Epoxied Bars					P	Pass			I	Inconclusive

See footnotes on page 42 for explanation of symbols and abbreviations.

Table 20. Barrier Evaluation Results, Cont.

State	Barrier	Anchorage	Ht	Shape	TL-3 Evaluation				TL-4 Evaluation			
					Ht	Str	Anch	Overall	Ht	Str	Anch	Overall
SC	Type 56SS	4-in. Pavement Keyway	56	SS	P	P	P*	Pass	P	P	P*	Pass
		End Anchor Footing					I	Inconclusive			I	Inconclusive
		Continuous Footing					P*	Pass			P*	Pass
		Cast-In or Epoxied Bars					P	Pass			I	Inconclusive
SD	Retrofit Bridge Rail	Reinforcement	32	O	P	I	I	Inconclusive	F	-	-	Fail
UT	Concrete Median	#5 Reinforcing Bars	42	SS	P	P*	P*	Pass	P	I	I	Inconclusive
	Half Constant Slope	#5 Reinforcing Bars	42	SS	P	I	I	Inconclusive	P	I	I	Inconclusive
	Constant Slope Median	#5 Reinforcing Bars	54	SS	P	P*	P*	Pass	P	I	I	Inconclusive
VA	F-Shape Median	Dowels	32	F	P	I	I	Inconclusive	F	-	-	Fail
		Monolithic Footing					I	Inconclusive			-	Fail
	F-Shape Half Section	Dowels	32	F	P	I	I	Inconclusive	F	-	-	Fail
		Monolithic Footing					I	Inconclusive			-	Fail
WI	Type S32	#8 Dowels (Typical)	32	SS	P	P	P*	Pass	F	-	-	Fail
		#5 Bent Bars (Bridge)					P	Pass			-	Fail
	Type S36	#8 Dowels (Typical)	36	SS	P	P	P*	Pass	P	P	I	Inconclusive
		#5 Bent Bars (Bridge)					P	Pass			P	Pass
	Type S42	#8 Dowels (Typical)	42	SS	P	P*	P*	Pass	P	I	I	Inconclusive
		#5 Bent Bars (Bridge)					P*	Pass			I	Inconclusive
	Type S56	#8 Dowels (Typical)	56	SS	P	P*	P*	Pass	P	I	I	Inconclusive
		#5 Bent Bars (Bridge)					P*	Pass			I	Inconclusive
WY	Shoulder Barrier	Dowel into Footing	42	SS	P	P	P*	Pass	P	I	I	Inconclusive
		Dowel into Slab					P	Pass			I	Inconclusive
		Monolithic Footing					P*	Pass			I	Inconclusive
	Median Barrier	Dowel into Footing	42	SS	P	P	P*	Pass	P	P	I	Inconclusive
		Dowel into Slab					P	Pass			I	Inconclusive
		Monolithic Footing					P*	Pass			P	Pass

See footnotes on page 42 for explanation of symbols and abbreviations.

Each barrier variation was evaluated in four areas: stability, shape, barrier strength, and anchorage strength. Figure 27 depicts the evaluation results for each criterion. Significant observations include:

- The minimum barrier height was 32 in., and therefore, all 85 variations had sufficient height for TL-3 stability.
- The only "failed" evaluations were TL-4 stability for the 18 barrier variations with heights below 34 in. In addition, three 34-in. tall variations were considered "inconclusive" for TL-4 stability. In total, 21 variations did not pass TL-4 stability and were not evaluated for any other TL-4 criteria.
- All shape evaluations were satisfactory.
- Strength and anchorage were the most frequent "inconclusive" evaluations. This was partly due to the limitations of computational analysis methods and the availability of suitable crash test data for direct comparison. Future research into concrete barrier reinforcement and anchorage details may enable some of these barriers to be justified as crashworthy to MASH TL-3 or TL-4.

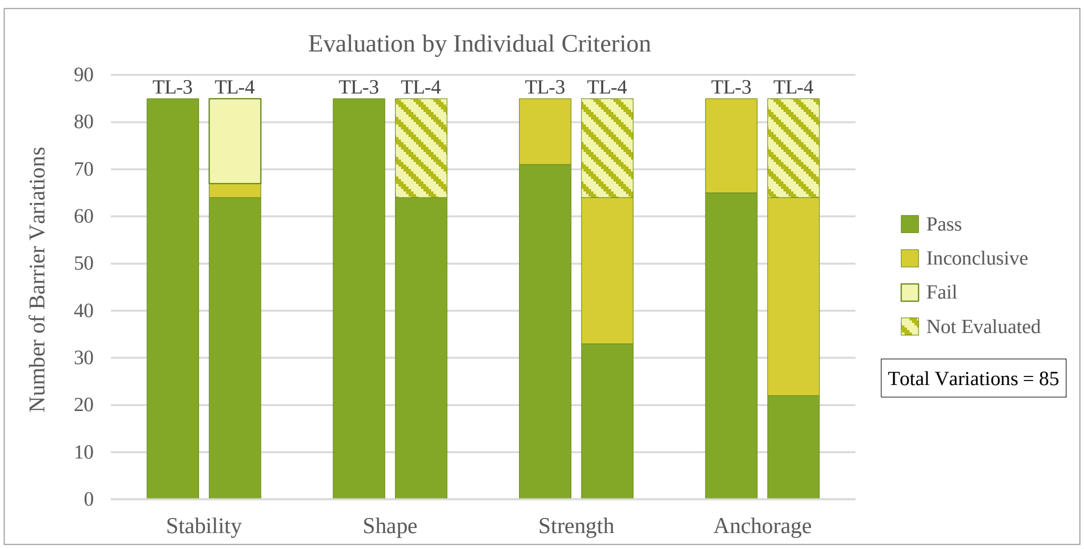

Figure 27. Assessment Results for Stability, Shape, Strength, and Anchorage

Since strength and anchorage often controlled the overall evaluation, Figure 28 looks at barrier reinforcement pattern versus the overall evaluation and Figure 29 does the same for anchorage configuration. Significant observations from the reinforcing and anchorage plots include:

- Most of the barrier variations deemed crashworthy at MASH TL-3 had both longitudinal and vertical reinforcement.
- Only variations with both longitudinal and vertical reinforcement were deemed crashworthy at MASH TL-4. Current research and crash test data are insufficient to justify the TL-4 performance of minimally reinforced or unreinforced barriers.

- Barrier variations with rebar, dowel, keyway, and footing anchorages fared well in TL-3 evaluations. Of barriers evaluated for TL-4 (i.e., barriers 36 in. or taller), the rebar and footing configurations also did well in TL-4 evaluations.

- No dowel-anchored barriers and very few keyway-anchored barriers were evaluated as crashworthy at TL-4. These anchorages may have sufficient strength at TL-4, but current research and crash test data are insufficient to justify this performance.

- The "other" anchorage category included end anchor footings, retaining structures, and other atypical configurations which, unsurprisingly, were difficult to evaluate conclusively.

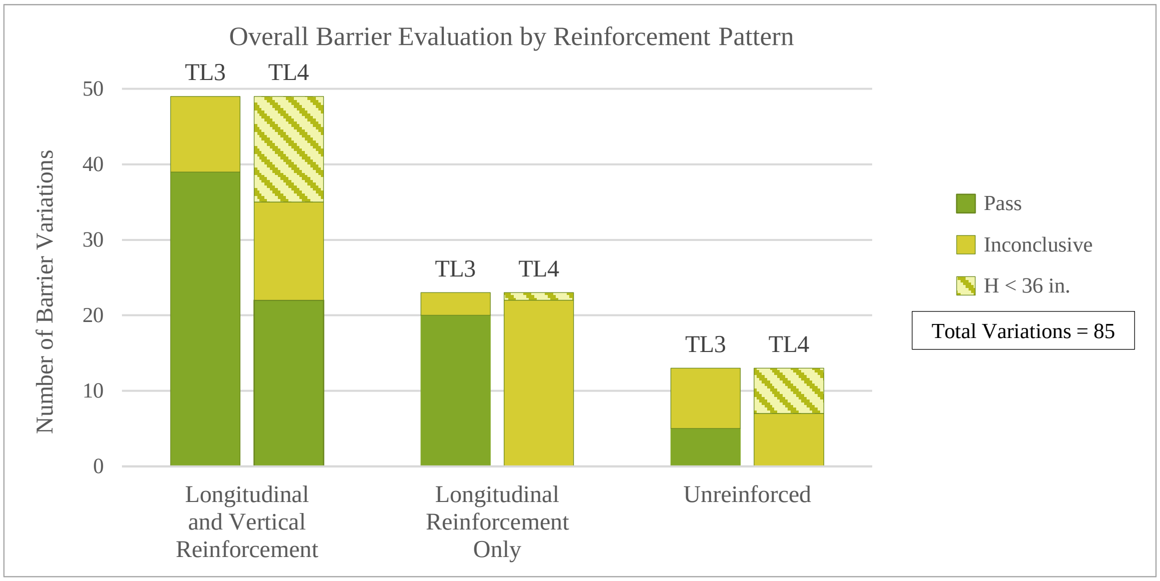

Figure 28. Overall Evaluations Grouped by Barrier Reinforcement Pattern

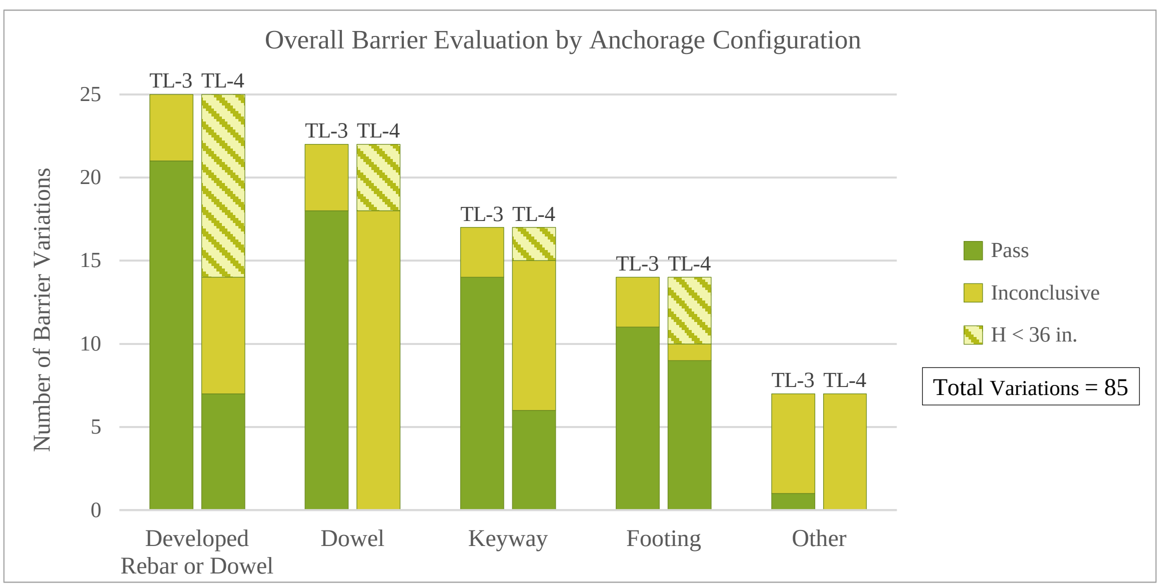

Figure 29. Overall Evaluations Grouped by Barrier Anchorage Configuration

5 DESIGN STRENGTH ANALYSIS

After the completion of the permanent concrete barrier evaluations, the calculated yield line theory and punching shear strengths were compiled and analyzed to better understand the performance of the current DOT standards to these requirements. The results were plotted against the required strength at TL-3 or TL-4 for various barrier heights.

5.1 Yield Line Theory Strength

After evaluations for all the barriers were completed, results from the yield line analyses were compiled and organized into interior and end section subsets. The results were also filtered into two barrier height ranges: heights less than 36 in. and heights greater than or equal to 36 in. These ranges were selected based on the 36-in. height requirement for stability at MASH TL-4. The barrier strengths were then plotted based on cantilever wall flexural strength (M_c) versus the wall flexural strength (M_w), as seen in Figures 30 through 33. These plots also contain design curves for required combinations of M_c and M_w at various barrier heights based on the design impact forces summarized in Table 17.

Some of the barriers submitted for evaluation did not include end section details. For purposes of the strength evaluation, the end sections of these barriers were analyzed using the interior section details. However, barriers submitted without end section details were not included in this analysis or in the figures below. As seen in Figures 30 through 33, very few of the permanent concrete barriers that could be computationally analyzed utilizing yield line theory lacked adequate strength to resist impacts at the relevant MASH test level. Most of barriers detailed with both longitudinal and vertical reinforcement had calculated strengths much greater than required. This suggests that many DOTs could revisit their reinforced barrier details and potentially realize cost savings in barrier construction.

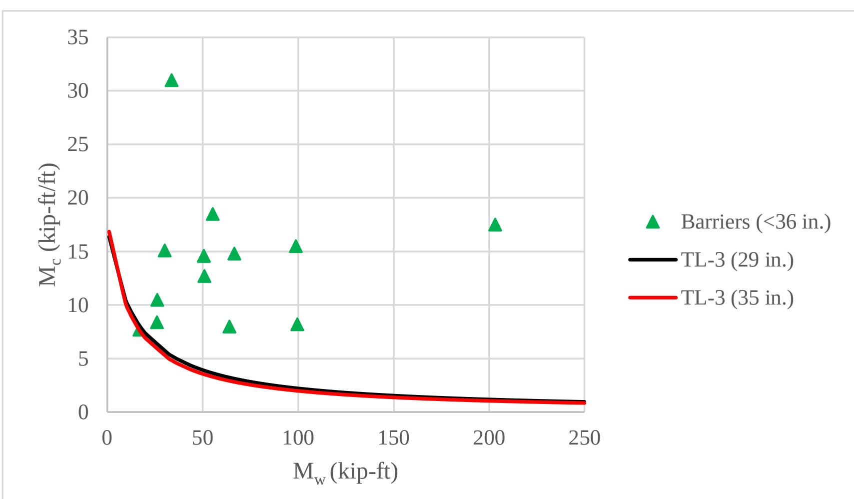

Figure 30. Yield Line Analysis of Interior Sections Assessed to MASH TL-3

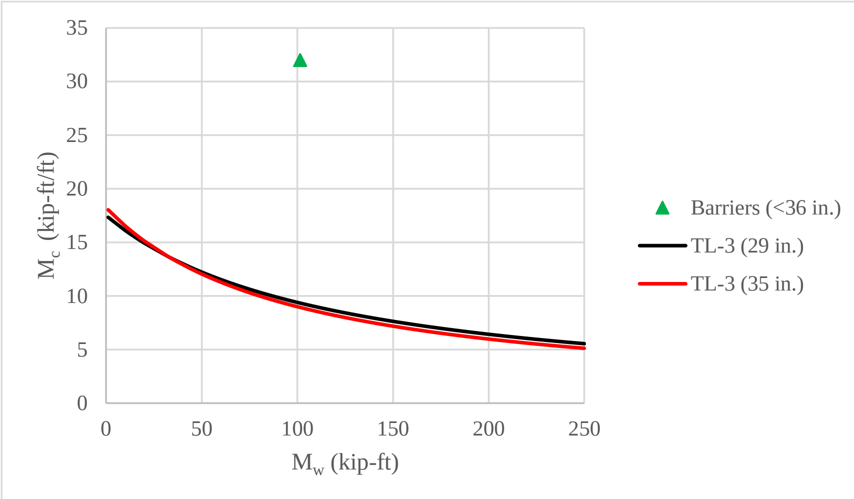

Figure 31. Yield Line Analysis of End Sections Assessed to MASH TL-3

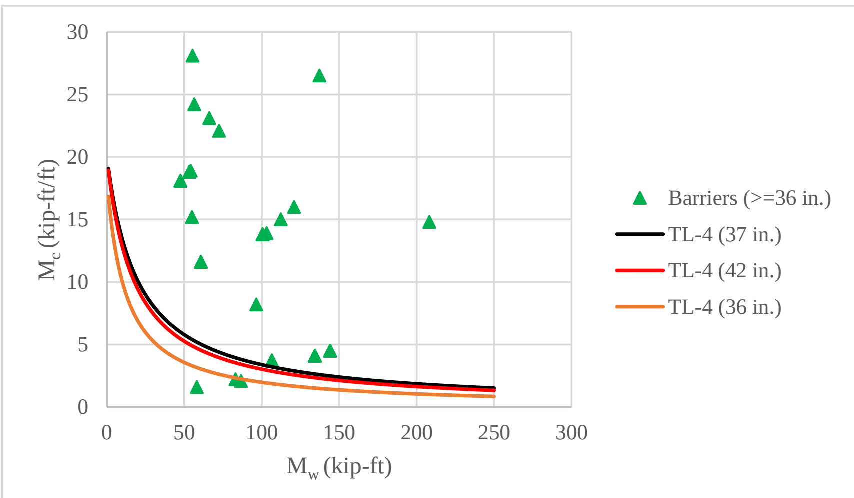

Figure 32. Yield Line Analysis of Interior Sections Assessed to MASH TL-4

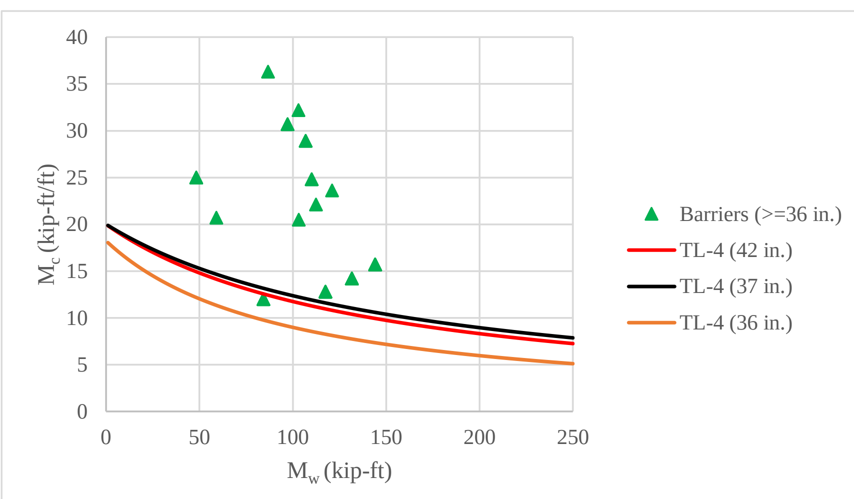

Figure 33. Yield Line Analysis of End Sections Assessed to MASH TL-4

Several states submitted details for unreinforced barriers or barriers without vertical reinforcement at interior sections. Testing conducted to MASH TL-3 on an unreinforced barrier in test no. OSSB-1 [22] suggests favorable performance despite lack of reinforcement. However, the understanding of unreinforced barrier impact behavior is limited and few evaluation methods aside from full-scale crash testing exist for these types of barriers. Recent efforts have been made to create a more optimized design for a MASH TL-4 concrete post-and-beam barrier [45] and similar studies could produce optimized designs for other permanent concrete barrier types.

5.2 Punching Shear Strength

Results from the punching shear computational analyses for all barriers were compiled and sorted based on interior and end section results. As seen in Figures 34 and 35, all the evaluated barriers met the strength requirements for punching shear. In the figures, the design loads from Table 17 are represented by the horizontal "limits" line.

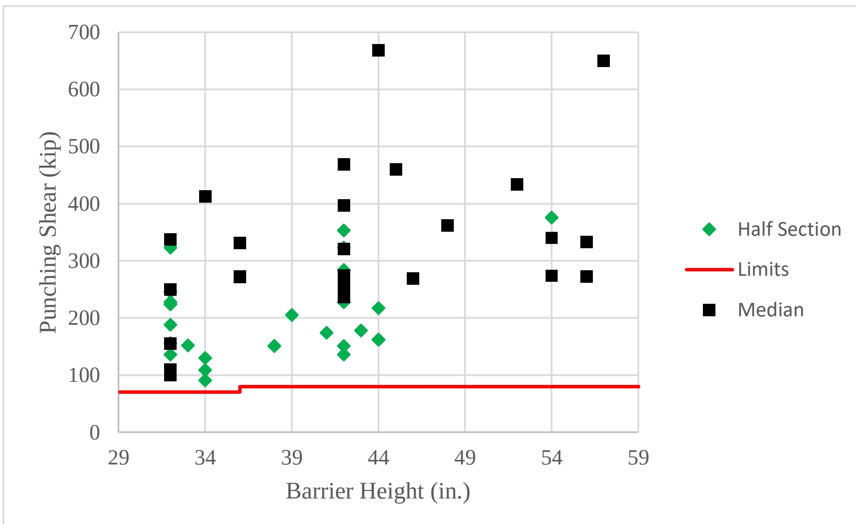

Figure 34. Interior Section Punching Shear Strength Results

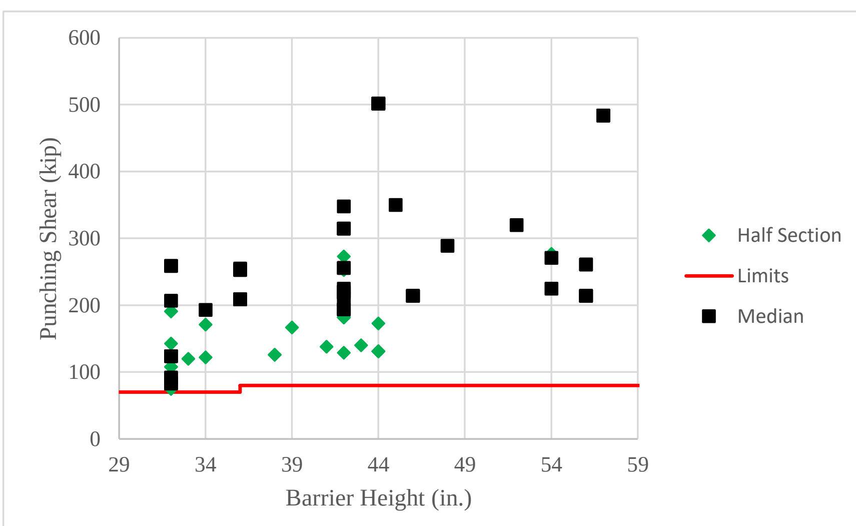

Figure 35. End Section Punching Shear Strength Results

Generally, the calculated punching shear strengths were at least 30 kips greater than required. Half section barriers were observed to be 292 percent and 230 percent overdesigned for interior and end sections, respectively. Median barriers were observed to be 447 percent and 350 percent overdesigned for interior and end sections, respectively. This shows that punching shear was generally not a critical failure mode. However, punching shear failures have been observed in physical tests, particularly for safety shapes, and so this limit state should be afforded due consideration in barrier strength evaluations.

Additionally, the data shows that half section barriers generally possessed a reduced punching shear strength in comparison to the median barriers. This result is to be expected because the punching shear strength is based solely on the concrete strength of the barrier per AASHTO guidance, and concrete strength is directly correlated to the thickness of the concrete barrier. Therefore, since median barriers are generally thicker than half-section barriers, it is expected that they would exhibit greater punching shear strength. Also, it appears from the data that because of their reduced strength, the half-section barriers are more susceptible for punching shear. Therefore, it is more critical that these barriers be checked for punching shear failures.

The data also shows that end sections have a lower punching shear strength than interior sections. This finding was also expected due to only a two-plane critical perimeter at end section calculations versus a three-plane critical perimeter for interior sections. Therefore, punching shear strength of end sections is more critical than that of interior sections.

Additionally, it appears that as the height of a barrier increases beyond 36 in. the punching shear strength also increases. This is likely due to the effective impact load height remaining at 30 in. for all barriers taller than 36 in. Thus, the vertical sides of the critical perimeter for calculating punching shear strength continue to increase in length as the barrier increases in height.

5.2.1 Top-Down Punching Shear Approach

Based on the observed design overstrength as discussed in Section 5.2 an alternate punching shear analysis was explored. The premise of the alternate investigation was based on the vertical distribution of a forces during a MASH TL-4 impact reported from simulations as part of NCHRP Project 22-20(2) [8]. The vertical distribution of impact forces on a 42-in. barrier was recreated from that report using a plot digitizer and is displayed in Figure 36.

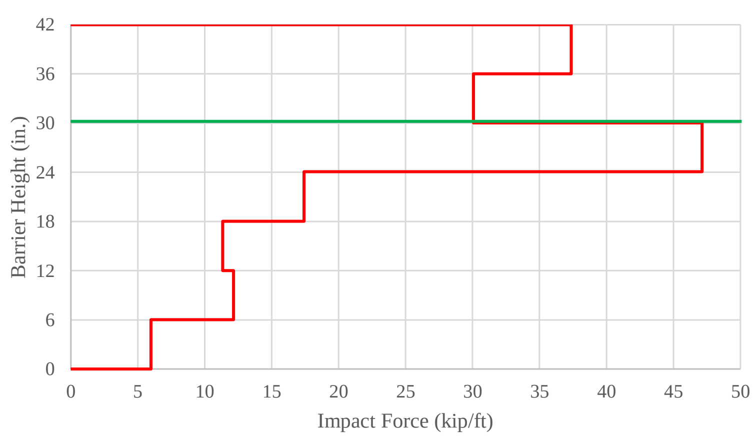

Figure 36. Vertical Distribution of Impact Forces on a 42-in. Vertical Barrier [8]

The load distribution extends below the effective height, H_e. However, the top of the barrier is expected to be the most critical in terms of punching shear failure due to the minimal critical perimeter. Therefore, a top-down punching shear approach was used to investigate punching shear through a sequence of increasing load patches and corresponding resisting breakout prisms. The analysis was performed by calculating the impact forces for the upper 6 and 12 in. of a 42-in. barrier, which resulted in total applied loads of 18.7 kips and 33.6 kips, respectively. Conservative approximations of 20 kips and 35 kips were used in subsequent calculations and were applied as area loads, rather than as a line load. The loaded area was defined as the longitudinal impact length (L_t) multiplied by either 6 in. or 12 in. A MASH TL-4 evaluation has a recommended longitudinal impact length of 5 ft for a 42-in. permanent concrete barrier.

The investigation was conducted on the Missouri Department of Transportation Type C single-slope permanent concrete barrier as an example. The details of the Type C barrier are shown in Figure 37. The barrier is specified to be constructed with a minimum concrete compressive strength of 4 ksi and is 8 in. wide at the top of the barrier.

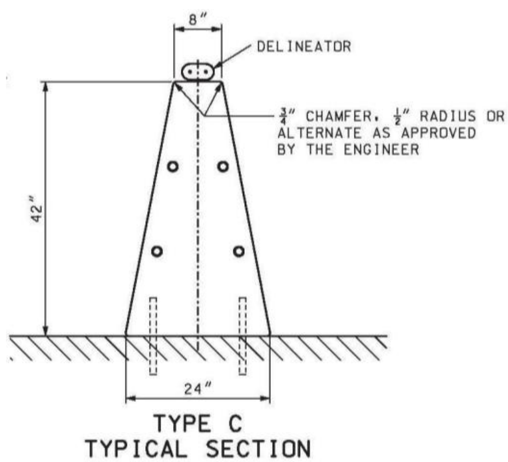

Figure 37. Missouri DOT Type C Single-Slope Permanent Concrete Barrier Details [46]

The punching shear strength of this barrier for the described area loads was determined to be 196 kips and 269 kips at interior sections and 167 kips and 220 kips at end sections for patch loads on the upper 6 in. and 12 in. of the barrier, respectively. The results from the punching shear analysis showed that the barrier still possessed punching shear resistance far greater than what would be needed to resist impacts. Therefore, the barrier would easily be expected to possess the resistance to punching shear for the reduced loads of 20 kips and 35 kips. The top thickness of the barrier would need be significantly reduced or a much lower strength concrete would need to be specified for punching shear resistance to become critical.

6 FUTURE RESEARCH

Of the 85 evaluated barrier variations, 45 were designated "inconclusive" at TL-4 and ten of these barriers remained inconclusive when reevaluated at TL-3. In many cases, this stemmed from the limited body of knowledge related to the performance of: (1) longitudinally or vertically unreinforced concrete barriers and (2) anchorage systems other than developed reinforcement. The limited existing research has been promising and suggests that unreinforced barriers and anchorage systems such as asphalt keyways, footings, and dowel bars may be crashworthy at MASH TL-3 or TL-4. However, more research and crash testing are needed if these barrier systems are to be justified as crashworthy by computation or comparison.

6.1 Unreinforced Barriers

Of the 19 states that submitted plans for evaluation, nine states provided details for fully unreinforced or vertically unreinforced barrier systems. This reinforcement detailing was significant because yield line theory is only applicable when both longitudinal and vertical reinforcement are present. Without a yield line strength calculation, barriers had to be evaluated by direct comparison. However, only two relevant crash tests were found: MASH test designation no. 3-11 on a fully unreinforced barrier and MASH test designation no. 3-10 on a vertically unreinforced barrier. This small pool of data meant that some barriers which may be crashworthy could not be justified as crashworthy. Further research into the impact behavior of unreinforced barriers could facilitate crashworthiness justifications for unreinforced barriers and could potentially inform the optimization of reinforced barrier details, yielding cost savings.

6.2 Dowel Anchorages

Many of the barriers submitted were anchored with the use of dowels. However, the anchorage strength required for a concrete barrier to perform adequately is currently unknown. Barriers with dowel anchorage had to be evaluated through comparisons to other crash tested barriers. Unfortunately, limited crash testing has been conducted on barriers with dowel anchorages, especially to MASH TL-4 criteria. As a result, many of the dowel anchored, TL-4 barriers were deemed to be inconclusive. Further research into the required anchorage strength for concrete barriers could aid in the evaluation of these "inconclusive" barriers and lead to better optimized designs.

6.3 Asphalt Keyway Anchorages

Keyway anchorages were the third most common anchorage configuration and were used in 17 of the 85 barrier variations. Asphalt keyways with depths between 1 and 3 in. were the most common keyway detail, but concrete and earthen keyways were also used. Barrier systems with 1-in. asphalt keyways have been tested once to MASH test designation 3-11 with an unreinforced single-slope barrier and twice to MASH test designation no 4-12 with a reinforced single-slope barrier. This sufficed to justify some reinforced barrier variations to MASH TL-4 and some unreinforced barrier variations to MASH TL-3. Interestingly, over half of the variations with a keyway anchorage were vertically unreinforced barriers that met MASH TL-4 stability requirements. However, given the current limited understanding of unreinforced concrete barrier behavior, the TL-4 asphalt keyway crash tests could not be used to justify the crashworthiness of vertically unreinforced barriers. Impact behavior in keyway systems is not well understood, and without this fundamental understanding, only systems that were very similar to the crash tested systems could be justified as crashworthy. Research into the performance of keyway anchorages, particularly asphalt keyways, would expand opportunities to justify the MASH TL-3 and TL-4 crashworthiness of barriers.

6.4 Grade Separated Median Barriers

As described in Section 2.5, there exists some research on the evaluation of grade separated barriers based on geotechnical analysis and FE simulations. However, no MASH crash testing was discovered during the literature review. With a high percentage of agencies providing details of such configurations, it is important to understand the impact behavior of these variations. Further investigation and crash testing of these barriers is needed.

6.5 Post-and-Beam Barriers

No post-and-beam barriers were evaluated as a part of this project. However, current AASHTO guidance does provide provisions for assessment of these systems utilizing a plastic analysis for strength and the charts shown in Figures 8 and 9 to assess snagging potential. Some justifications for the continued use of these charts have been reported as part of NCHRP Project 20-07(395). However, these charts are outdated and were originally created under the crash testing guidance and evaluation requirements of NCHRP Report 230. Therefore, due to changes in the vehicle fleet and testing criteria of MASH, updated guidance is needed. NCHRP Project 22-35 is currently underway and is expected to provide more information pertaining to this research need.

6.6 Textured and Aesthetic Barriers

As discussed in Section 2.7 guidelines have been developed and compiled in NCHRP Report 554 for the texturing of vertical and single-slope barriers. However, these guidelines were developed utilizing crash test data conducted under NCHRP Report 350. Previous recommendations for texturing on aesthetic barriers require revisitation to determine crashworthiness to MASH due to the more severe impact conditions between MASH and NCHRP Report 350 described in Section 2.1.

7 SUMMARY AND CONCLUSIONS

7.1 Summary

A literature review was conducted to identify the differences in crash testing parameters and evaluation criteria between NCHRP Report 350 and MASH with respect to permanent concrete barriers. Additionally, current evaluation methods other than crash testing of permanent concrete barriers were analyzed and documented. A crash testing database was compiled containing 41 MASH crash tests conducted on permanent concrete barriers of varying shapes, sizes, and anchorages. Sponsoring agencies were surveyed to acquire permanent concrete barrier system details. The survey responses were filtered, and a list was compiled to identify systems that conformed to the scope of this project. From the literature review and crash testing database, a methodology and evaluation criteria based on a barrier's height, shape, strength, and anchorage were determined, and 85 permanent concrete barrier variations were evaluated to MASH. When feasible, a computational evaluation of barrier strength was performed, and when conventional analysis was not feasible, barriers were compared to successfully crash-tested systems. Finally, areas of future research were identified that would create opportunities to justify existing barrier crashworthiness and to develop new, optimized barrier designs.

7.2 Conclusions

From the 85 evaluated barrier variations, 22 variations were evaluated as crashworthy at MASH TL-4 and an additional 42 variations were assessed as crashworthy when reevaluated at MASH TL-3. Strength and anchorage details were the most common source of "inconclusive" barrier assessments, and only rarely was this due to inadequate calculated capacity. Far more commonly, no computational method or suitable comparative crash tests were available to justify barrier performance. This particularly impacted the evaluations of barriers without vertical reinforcement and anchorage details such as keyways, dowels, and footings. These gaps in the body of knowledge represent research opportunities to expand the range of barrier configurations that can be conclusively evaluated for crashworthiness at both MASH TL-3 and TL-4.

Among barriers that were detailed with both longitudinal and vertical reinforcement, the barrier capacity calculated by yield line analysis often far exceeded the design load. This suggests that many DOTs could optimize their reinforced barrier details and potentially reduce construction costs. Punching shear analyses showed similar excess capacity, but both a traditional analysis and a more conservative top-down analysis indicated that punching shear will not commonly be a controlling limit state.

Many states submitted plans for unreinforced barriers or barriers with purely longitudinal reinforcing. While these barriers may be crashworthy to MASH TL-3 or TL-4, little research or crash testing currently exists for such barriers, and this often forced an "inconclusive" evaluation, particularly for MASH TL-4. Further research and crash testing are needed to develop an understanding of unreinforced barrier impact behavior. Barrier evaluations were also limited by the availability of research and crash testing for anchorage systems other than developed reinforcing. Roughly 70% of the evaluated barrier variations featured anchorage system details such as asphalt keyways, dowel bars, or footings that have minimal supporting evidence in literature. However, the available data is promising and suggests that further investments in research and crash testing to enhance understanding of anchorage options other than developed reinforcement would be worthwhile.

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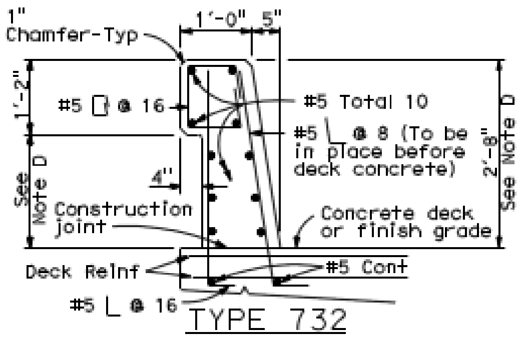
9 APPENDICES

The following sections provide MASH evaluations for various concrete barrier systems provided by the state departments of transportation that sponsored this project. These evaluations are thought to be conservative and are based on the available guidance, full-scale testing, and associated research available at the time this project was conducted. Any barrier with an overall evaluation of “inconclusive” may still be crashworthy to MASH, but further testing or analysis would be needed to justify the crashworthiness of the barrier.

Appendix A. California Permanent Concrete Barrier MASH Evaluations

A.1. MASH Equivalency of California DOT Type 732 Concrete Bridge Rail



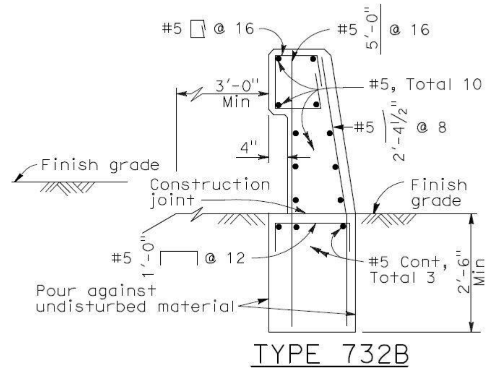


Figure A.1-1. California DOT Type 732 Bridge Rail Details [1]

Overview and Stability Evaluation

The California DOT Type 732 bridge rail is a 32-in. tall reinforced concrete barrier. The bridge rail has an 8.9-degree single-slope front face with a 14-in. by 12-in. top beam. The barrier is vertically reinforced with #5 bars spaced at 8-in. and longitudinally reinforced with five #5 bars spaced along both the front and back sides of the barrier. The top beam has additional vertical #5 stirrups spaced at 16 in. Anchorage for the Type 732 barrier is provided by extending the vertical #5 bars into the deck. The Type 732B configuration extends the vertical #5 bars into a 30-in. deep by 17-in. wide footing. Design details for the Type 732 bridge railing are shown in Figure A.1-1. This barrier has not been crash tested to MASH 2016 criteria, but it was previously crash tested to NCHRP Report 350 TL-4 [2].

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [3]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [4]. Thus, the 32-in. tall Type 732 barrier has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table A.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table A.1-1. Effective Loads for Design of MASH Barriers [10]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 158 kips for interior sections and 82 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 246 kips at interior sections and 191 kips at end sections. All calculated capacities were greater than the required 70 kips, and therefore, the Type 732 bridge rail satisfies MASH TL-3 loading criteria for interior and end sections.

Direct Comparison of Strength and Anchorage

The Type 732B barrier utilizes a concrete beam foundation. Currently, no computational methods exist for the analysis of this type of anchorage system. However, standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [11], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [12]. The details of these crashworthy barriers are compared to the details of the Type 732B foundations in Table A.1-2 and a schematic comparison of the system geometries is provided in Figure A.1-2.

Table A.1-2. California Type 732B Concrete Beam Foundation Comparison

Test Level	Test	Barrier Height	Base Width	Depth	Segment Length	Ditch Slope	Ditch Offset
TL-4	FE-1	36 in.	16 in.	33 in.	30 ft	1V:2H	1 ft
TL-4	FE-2	36 in.	18 in.	27 in.	50 ft	N/A	N/A
TL-4	FE-3	36 in.	13 in.	10 in.	50 ft	N/A	N/A
TL-3	CT	32 in.	24 in.[(a)]	10 in.	20 ft	1.5V:2H	2 ft
California Type 732B		32 in.	17 in.	30 in.	Unspecified	Unspecified	3 ft

N/A – Not Applicable, FE – Finite Element Analysis, CT – Crash Test
(a) Foundation is battered to match slope of barrier.

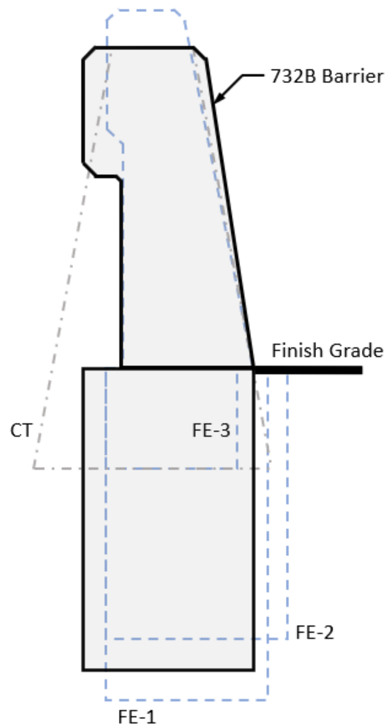


Figure A.1-2. California Type 732B Geometry Comparison

The Type 732B barrier foundation has similar geometry to the systems found crashworthy to MASH TL-4 in simulations FE-1 and FE-2. From the standpoint of a MASH TL-3 evaluation, the geometric differences were considered negligible. Therefore, the Type 732B concrete beam foundation is believed to be in compliance with MASH TL-3 when a segment length of at least 50 ft is provided in strong soil conditions.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Type 732 and 732B barriers are believed to be crashworthy and in compliance with MASH TL-3. The evaluations are summarized in Tables A.1-3 and A.1-4.

Table A.1-3. California Type 732 Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	TL-4
Stability		Height = 32 in.		≥ 30 in. Pass	≥ 36 in. Fail
Shape		Single-Slope		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	158 kips	≥ 70 kips Pass	
		End	82 kips		
	Punching Shear	Interior	246 kips		
		End	191 kips		
	Anchorage	Reinforcement		Pass	
Overall MASH Evaluation				Pass	Fail

Table A.1-4. California Type 732B Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	TL-4
Stability		Height = 32 in.		≥ 30 in. Pass	≥ 36 in. Fail
Shape		Single-Slope		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	158 kips	≥ 70 kips Pass	
		End	82 kips		
	Punching Shear	Interior	246 kips		
		End	191 kips		
	Anchorage	Footing (50-ft Segment Length)		Pass*	
Overall MASH Evaluation				Pass	Fail

* Justified based on available crash tests or finite element simulations.

A.1.1 References

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12. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

A.2. MASH Equivalency of California DOT Type 732SW Bridge Rail

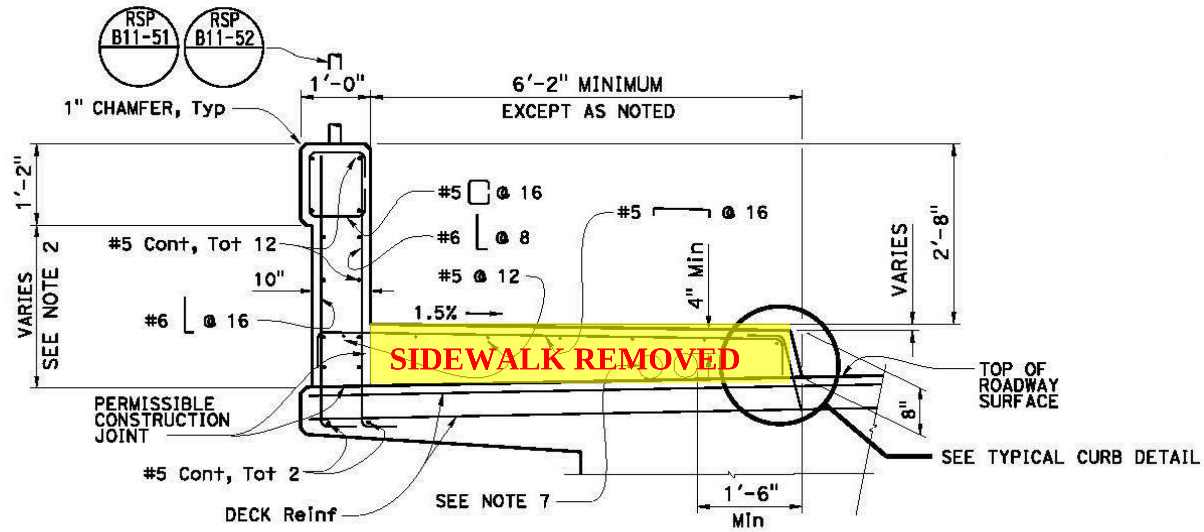

Figure A.2-1. California DOT Type 732SW Bridge Rail Details [1]

Overview and Stability Evaluation

The California DOT Type 732SW is a 41-in. tall reinforced concrete bridge rail with a vertical traffic face and a 14-in. by 12-in. top beam. The barrier is vertically reinforced with #6 bars spaced at 8 in. on the front face and 16 in. on the back face. Longitudinal reinforcement is provided by twelve #5 reinforcing bars on both the front and back sides of the barrier, four of which are in the top beam. In addition, the top beam has vertical #5 stirrups spaced at 16 in. Anchorage is provided by extending the vertical reinforcement into the deck. Design details for the Type 732SW are shown in Figure A.2-1. The details show a 32-in. barrier height, but the barrier was evaluated with the sidewalk removed, increasing the barrier height to 41 in. This railing has been crash tested with the sidewalk in test nos. 130MASH3C13-02, 130MASH3P13-01, and 110MASH2C14-01 [1] and met MASH TL-3 standards.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3-4]. Thus, the 41-in. Type 732SW barrier with sidewalk removed has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Multiple full-scale MASH crash tests have been conducted on barriers with vertical traffic face geometry. Vertical-face concrete barriers with heights ranging from 32 in. to 34 in. have satisfied MASH safety performance criteria in tests with both small car and pickup truck vehicles [5–8]. Therefore, a vertical traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table A.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table A.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 217 kips for interior sections and 118 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 174 kips at interior sections and 138 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the Type 732SW barrier satisfies MASH TL-4 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the California Type 732SW Bridge Rail with sidewalk removed is believed to be crashworthy and in compliance with MASH TL-4. The evaluation is summarized in Table A.2-2.

Table A.2-2. California Type 732SW with Sidewalk Removed Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 41 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Vertical</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>217 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 80 kips
Pass</td></tr>
<tr><td>End</td><td>118 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>174 kips</td></tr>
<tr><td>End</td><td>138 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Pass</td><td>Pass</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Pass</td></tr>
</table>

A.2.1 References

1. Whitesel, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 732SW Bridge Rail*, FHWA/CA15-2181, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, September 2016.

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

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6. Whitesel, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 732SW Bridge Rail*, FHWA/CA15-2181, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, September 2016.

7. Williams, W.F., Bligh, R.P., Menges, W.L., *MASH Test 3-11 of the TxDOT T222 Bridge Rail*, FHWA/TX-14/9-1002-12-13, Texas Transportation Institute, College Station, TX, July 2016.

8. Bligh, R.P., Briaud, J.L., Kim, K.M., Abu-Odeh, A., *Design of Roadside Barrier Systems on MSE Retaining Walls*, National Cooperative Highway Research Program (NCHRP) Report 22-20, Texas Transportation Institute, College Station, TX, November 2009.

9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

Appendix B. Florida Permanent Concrete Barrier MASH Evaluations

B.1. MASH Equivalency of Florida DOT 38-in. Curb and Gutter Concrete Barrier and 38-in. Shoulder Concrete Barrier

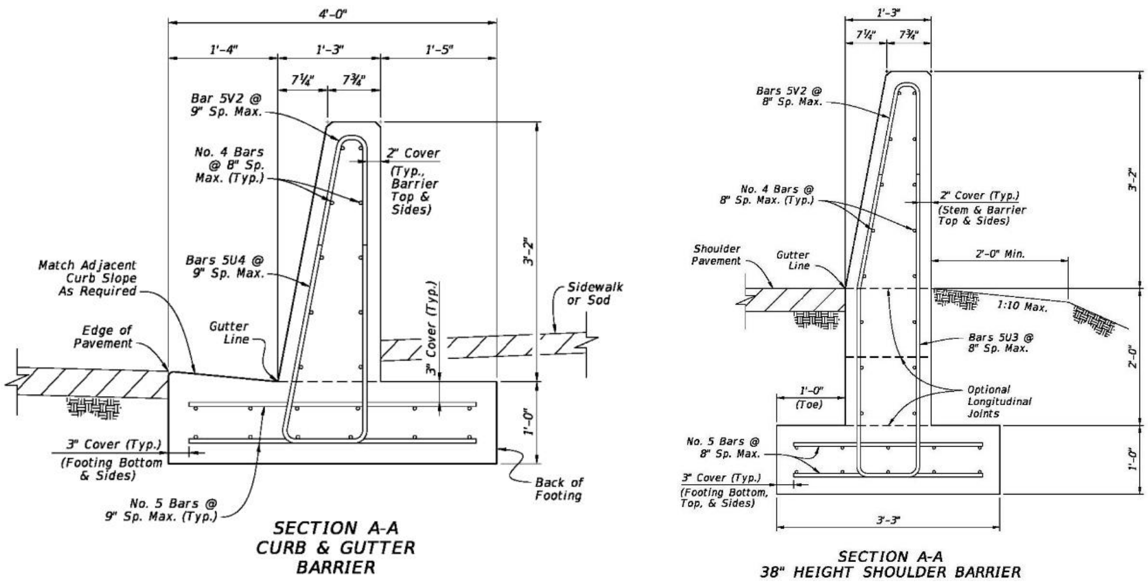


Figure B.1-1. Florida DOT 38-in. Curb and Gutter Barrier and 38-in. Shoulder Barrier [1]

<u>Overview and Stability Evaluation</u>

The Florida DOT 38-in. Curb and Gutter Barrier and 38-in. Shoulder Barrier are 38-in. tall reinforced concrete barriers with a 10.8-degree single-slope traffic face. Both barriers are vertically reinforced with #5 bars spaced at 9 in. The vertical reinforcement is anchored into a reinforced concrete footing. The barrier is longitudinally reinforced with five #4 bars on both the front and back sides of the rail. Design details for both configurations of the 38-in. barrier are shown in Figure B.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 38-in. Curb and Gutter Barrier and 38-in. Shoulder Barrier have the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5-7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table B.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table B.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 159 kips for interior sections and 120 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 151 kips at interior sections and 126 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the barrier satisfies MASH TL-4 loading criteria for interior and end sections.

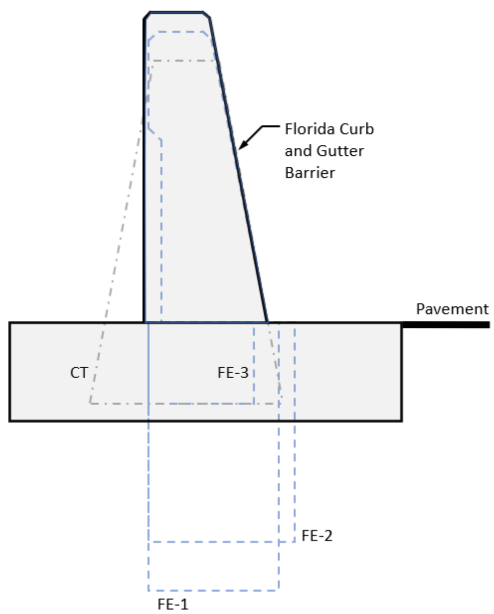
Direct Comparison of Strength and Anchorage

Both the Curb and Gutter Barrier and the Shoulder Barrier utilize a footing foundation. Currently, no computational methods exist for the analysis of this type of anchorage system. However, standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [10], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [11]. The details of these crashworthy barriers are compared to the foundation details of the Curb and Gutter Barrier and the Shoulder Barrier in Table B.1-2 and a schematic comparison of the system geometries is provided in Figure B.1-2.

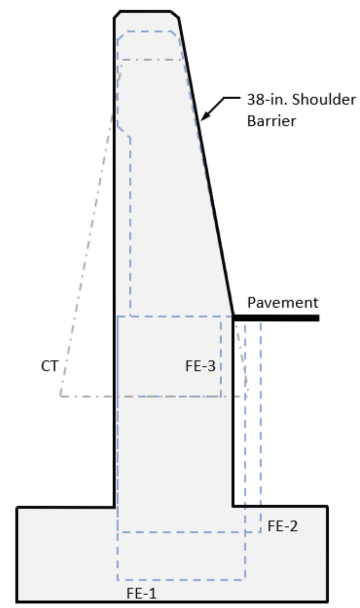
Table B.1-2. Florida 38-in. Barrier Concrete Beam Foundation Comparison

Test Level	Test	Barrier Height	Base Width	Depth	Segment Length	Ditch Slope	Ditch Offset
TL-4	FE-1	36 in.	16 in.	33 in.	30 ft	1V:2H	1 ft
TL-4	FE-2	36 in.	18 in.	27 in.	50 ft	N/A	N/A
TL-4	FE-3	36 in.	13 in.	10 in.	50 ft	N/A	N/A
TL-3	CT	32 in.	24 in.[(a)]	10 in.	20 ft	1.5V:2H	2 ft
Florida Curb and Gutter Barrier		38 in.	48 in.	12 in.	Unspecified	N/A	N/A
Florida Shoulder Barrier		38 in.	39 in.	36 in.	Unspecified	1V:10H	0 ft

N/A – Not Applicable, FE –Finite Element Analysis, CT – Crash Test
(a) Foundation is battered to match slope of barrier.



Curb and Gutter Barrier Comparison



Shoulder Barrier Comparison

Figure B.1-2. Florida 38-in. Barriers Geometry Comparison

The simulations conducted on concrete barriers with standalone beam foundations resulted in minimal system displacement, and the 10000S test vehicle was successfully contained and redirected according to MASH TL-4. Note that the simulations modeled soil conditions representative of those found at the Texas Transportation Institute Proving Ground. The Florida Shoulder Barrier footing has a larger width and depth than any of the simulated beam foundations and includes both a toe and heel, which further increases the strength. The minimum segment length in the simulations was 30 ft, and therefore, this MASH evaluation applies to systems with segment lengths of at least 30 ft.

The Florida Curb and Gutter Barrier footing has a similar depth to the system in simulation FE-3 and a larger width than any of the simulated foundations. The increased width and the presence of a toe and heel in the Curb and Gutter Barrier footing are expected to increase the impact resistance compared to the simulated system. Because simulation FE-3 forms the basis of the justification, this MASH evaluation applies to systems with segment lengths of at least 50 ft.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Florida 38-in. Curb and Gutter Barrier is believed to be crashworthy and in compliance with MASH TL-4 when a minimum 50 ft segment length is provided for installations in strong soil conditions and with a slope break no closer than 1 ft from the back face and a soil slope no greater than 1V:2H. The Shoulder Barrier is believed to be crashworthy and in compliance with MASH TL-4 when a minimum 30 ft segment length is provided in strong soil conditions with no slope break close to the back face. The evaluations are summarized in Tables B.1-3 and B.1-4.

Table B.1-3. Florida 38-in. Curb and Gutter Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 38 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	159 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	120 kips		
	Punching Shear	Interior	151 kips		
		End	126 kips		
	Anchorage	Footing (50-ft Segment Length) Slope Break ≥ 1 ft from Back Max Slope 1V:2H		Pass*	Pass*
Overall MASH Evaluation				Pass	Pass

* Justified based on available crash tests or finite element simulations.

Table B.1-4. Florida 38-in. Shoulder Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 38 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	159 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	120 kips		
	Punching Shear	Interior	151 kips		
		End	126 kips		
	Anchorage	Footing (30-ft Segment Length) in Level Terrain		Pass*	Pass*
Overall MASH Evaluation				Pass	Pass

* Justified based on available crash tests or finite element simulations.

B.1.1 References

1. *FY 2019-20 Standard Plans*, Florida Department of Transportation, Tallahassee, FL, November 1, 2018.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.

7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.

9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

10. Sheikh, N.M., Bligh, R.P., Kovar, J.C., Cakalli, S., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of Structurally Independent Foundations for 36-inch Tall Single-Slope Traffic Rail (SSTR) for MASH TL-4*, FHWA/TX-19/0-6968-R7, Texas Transportation Institute, College Station, TX, October 2019.

11. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

B.2. MASH Equivalency of the Florida DOT 44-in. Single-Slope Shoulder Barrier

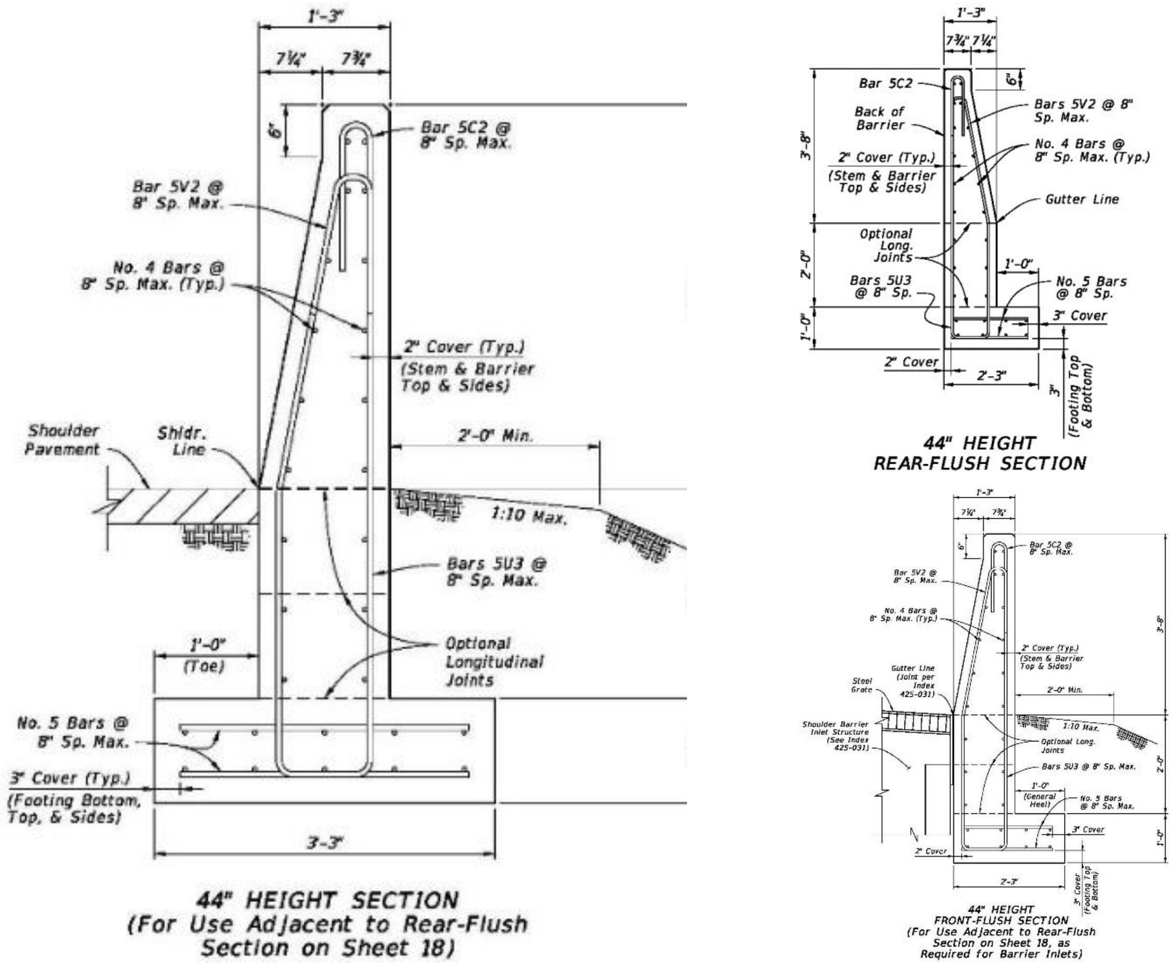


Figure B.2-1. Florida DOT Single-Slope Shoulder Barrier Details [1]

<u>Overview and Stability Evaluation</u>

The Florida DOT Single-Slope Shoulder Barrier is a 44-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face. The barrier is vertically reinforced with #5 stirrups at an 8-in. critical spacing, and longitudinally reinforced by six #4 bars on both the front and back sides of the barrier. Anchorage is provided by tying the barrier into one of three footing variations: typical, front-flush, or rear-flush. Design details for the Florida DOT Single-Slope Shoulder Barrier are shown in Figure B.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 44-in. Shoulder Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

The 6-in. vertical section at the top of the barrier deviates from the typical single-slope traffic face. This deviation would not affect the ability of the barrier to redirect test vehicles but may increase the potential for the occupant's head to contact the barrier during an impact event. Although the risk is difficult to determine, it is believed that the variation would not significantly increase risk to the occupant, and therefore, would be acceptable according to MASH criteria.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table B.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table B.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 179 kips for interior sections and 98 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 162 kips at interior sections and 131 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the Shoulder Barrier satisfies MASH TL-4 loading criteria for interior and end sections.

Direct Comparison of Strength and Anchorage

The Florida 44-in. Shoulder Barrier utilizes a footing foundation. Currently, no computational methods exist for the analysis of this type of anchorage system. However, standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [10], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [11]. The details of these crashworthy barriers are compared to the 44-in. Shoulder Barrier foundations in Table B.2-2 and a schematic comparison of system geometries is provided in Figure B.2-2.

Table B.2-2. Florida 44-in. Shoulder Barrier Foundation Comparison

Test Level	Test Type	Barrier Height	Base Width	Depth	Segment Length	Ditch Slope	Ditch Offset
TL-4	FE	36 in.	16 in.	33 in.	30 ft	1V:2H	1 ft
TL-4	FE	36 in.	18 in.	27 in.	50 ft	N/A	N/A
TL-4	FE	36 in.	13 in.	10 in.	50 ft	N/A	N/A
TL-3	CT	32 in.	24 in.(a)	10 in.	20 ft	1.5V:2H	2 ft
Typical Shoulder Barrier		44 in.	39 in.	36 in.	Unspecified	1V:10H	0 ft
Front-Flush Shoulder Barrier		44 in.	27 in.	36 in.	Unspecified	1V:10H	0 ft
Rear-Flush Shoulder Barrier		44 in.	27 in.	36 in.	Unspecified	N/A	N/A

N/A – Not Applicable, FE –Finite Element Analysis, CT – Crash Test
(a) Foundation is battered to match slope of barrier.

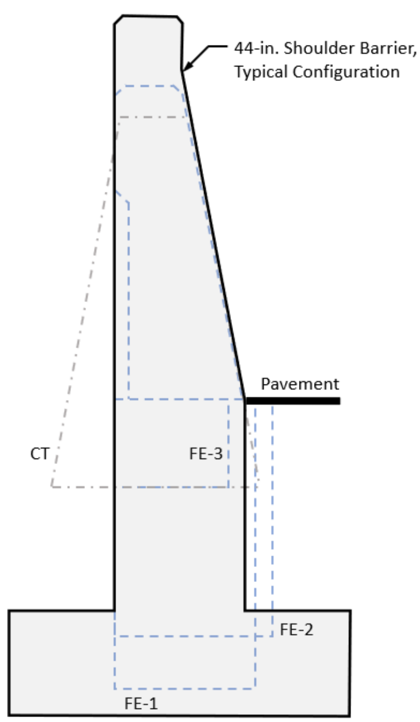


Figure B.2-2. Florida 44-in. Shoulder Barrier, Foundation Cross Section Comparison

The simulations conducted on concrete barriers with standalone beam foundations resulted in minimal system displacement and the 10000S test vehicle was successfully contained and redirected according to MASH TL-4. Note that the simulations modeled soil conditions representative of those found at the Texas Transportation Institute Proving Ground. All three of the Florida 44-in. Shoulder Barrier foundations have a larger base width and depth than the simulated beam foundations. Additionally, the Shoulder Barrier footings are configured with a toe or heel, which would further increase their strength. Therefore, the shoulder barrier foundations are believed to provide adequate strength to resist MASH TL-4 impact loads. The minimum segment length in the simulations was 30 ft, and therefore, this MASH evaluation applies to systems with segment lengths of at least 30 ft.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, all three configurations of the Florida DOT 44-in. Shoulder Barrier are believed to be crashworthy and in compliance with MASH TL-4 with a segment length of 30 ft or greater in strong soil conditions and with sufficient soil fill behind the barrier. The barrier evaluation is summarized in Table B.2-3.

Table B.2-3. Florida 44-in. Shoulder Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 44 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="7">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>179 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 80 kips
Pass</td></tr>
<tr><td>End</td><td>98 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>162 kips</td></tr>
<tr><td>End</td><td>131 kips</td></tr>
<tr><td rowspan="3">Anchorage</td><td colspan="2">Typical Footing (30-ft Segment)</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="2">Front-Flush Footing (30-ft Segment)</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="2">Rear-Flush Footing (30-ft Segment)</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Pass</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

B.2.1 References

1. *FY 2019-20 Standard Plans*, Florida Department of Transportation, Tallahassee, FL, November 1, 2018.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.
6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.
7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
10. Sheikh, N.M., Bligh, R.P., Kovar, J.C., Cakalli, S., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of Structurally Independent Foundations for 36-inch Tall Single-Slope Traffic Rail (SSTR) for MASH TL-4*, FHWA/TX-19/0-6968-R7, Texas Transportation Institute, College Station, TX, October 2019.
11. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

Appendix C. Georgia Permanent Concrete Barrier MASH Evaluations

C.1. MASH Equivalency of the Georgia DOT Type 2-S Concrete Barrier

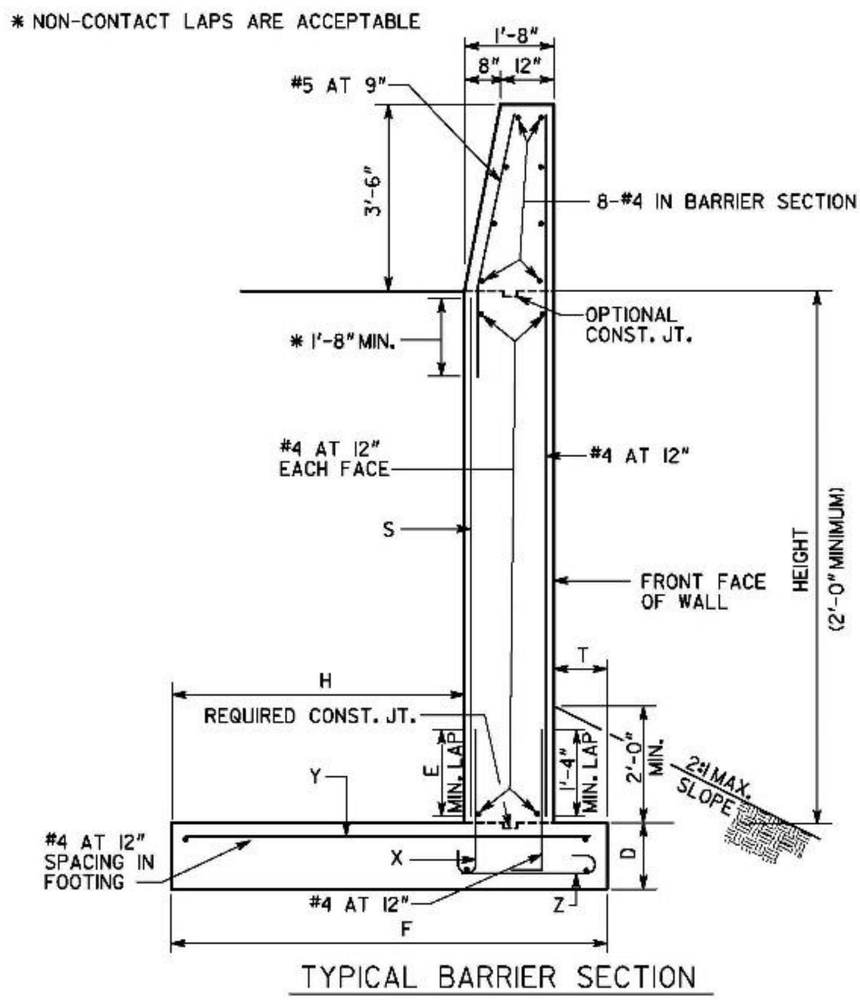


Figure C.1-1. Georgia DOT Type 2-S Concrete Barrier Details [1]

Overview and Stability Evaluation

The Georgia DOT Type 2-S Concrete Barrier is a 42-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face and a top width of 12 in. The barrier is vertically reinforced with #5 bars spaced at 9 in. and embedded into the retaining structure below. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier. The adequacy of the retaining wall configuration was not evaluated as part of this research effort. Design details for the Type 2-S Barrier are shown in Figure C.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. Type 2-S Concrete Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table C.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table C.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 216 kips for interior sections and 137 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 284 kips at interior sections and 22 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the shoulder barrier satisfies MASH TL-4 loading criteria for interior sections and end sections.

While the capacity of the single slope barrier appeared to meet MASH TL-4 requirements, the capacity of the retaining wall with respect to the combination of the soil retention loads and the impact loading of the barrier is unknown. Valid comparison with similar full-scale crash tested systems was not available, and calculation methods for this configuration were not available, Further research would be needed to verify the capacity of the barrier attached to the retaining wall foundation. Overall Evaluation

Based on this evaluation of height, geometry, and strength, the Georgia 42-in. Type 2-S Concrete Barrier section is believed to be crashworthy and in compliance with MASH TL-4. However, the adequacy of the retaining wall to resist impacts was not evaluated, and the MASH crashworthiness of the overall barrier system remains inconclusive. The evaluation is summarized in Table C.1-2.

Table C.1-2. Georgia Type 2-S Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 42 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>216 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 80 kips
Pass</td></tr>
<tr><td>End</td><td>127 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>284 kips</td></tr>
<tr><td>End</td><td>222 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">RC Retaining Wall</td><td>Inconclusive</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Inconclusive</td></tr>
</table>

C.1.1 References

1. Special Detail Concrete Side Barrier Types 2-S, 2-SA, 2-SB and 2-SC, Georgia Department of Transportation, Alanta, GA, December, 2017.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.
6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.
7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

C.2. MASH Equivalency of the Georgia Type 3-SA/SB Concrete Barrier

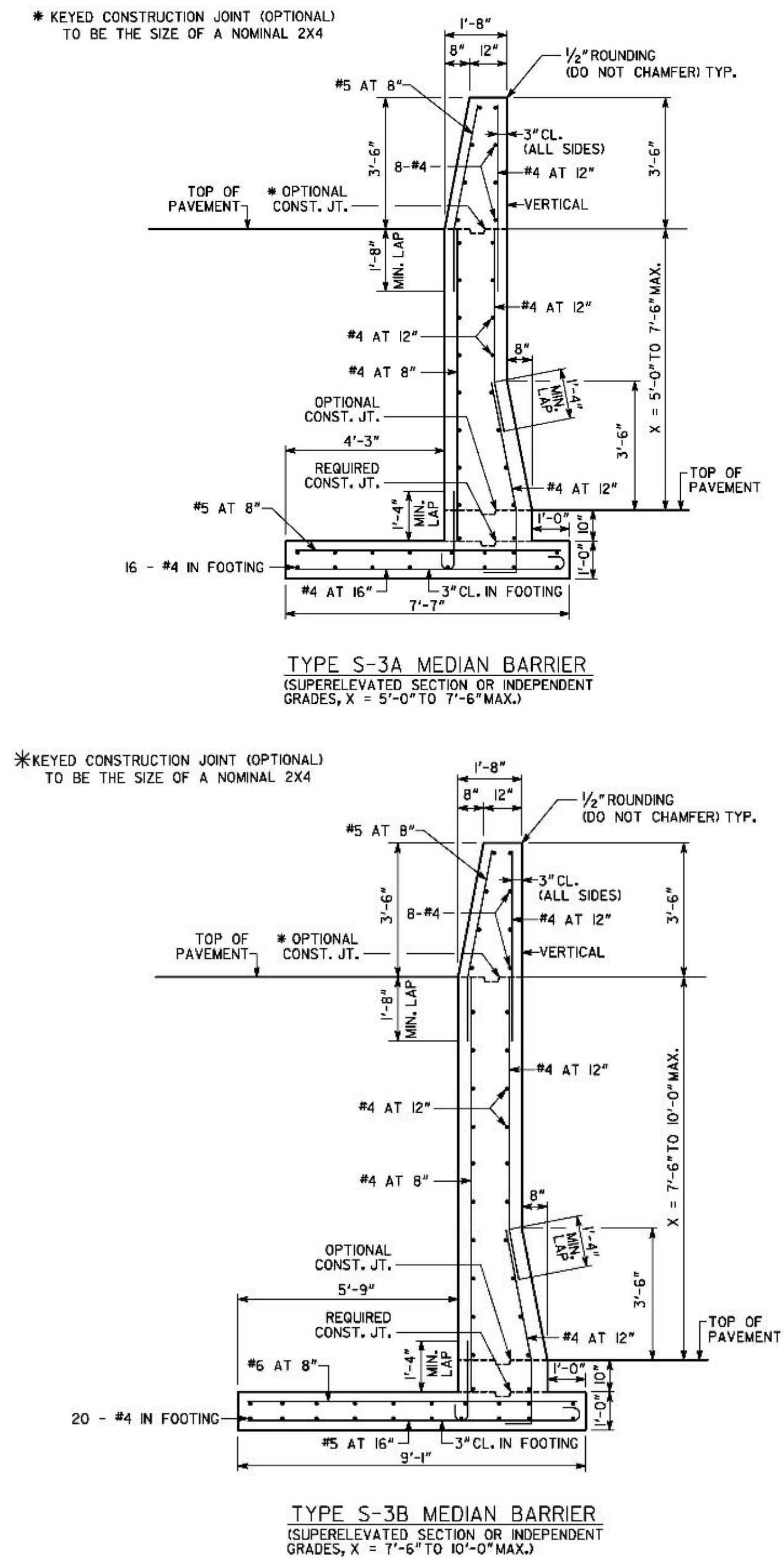


Figure C.2-1. Georgia DOT Type 3-SA/SB Single-Slope Barrier [1]

Overview and Stability Evaluation

The Georgia DOT Type 3-SA/SB barrier is a 42-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face. The front side of the barrier is vertically reinforced with #5 bars spaced at 8 in., and the back side is vertically reinforced with #4 bars spaced at 12 in. Longitudinal reinforcement consists of four #4 bars on both the front and back sides of the barrier. The vertical reinforcement is embedded into the retaining wall system below the barrier. The adequacy of the two retaining wall configurations was not evaluated as part of this research effort. Design details for the 42-in. barrier with both retaining wall configurations are shown in Figure C.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall Type 3-SA/SB barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table C.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table C.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 232 kips for interior sections and 137 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 284 kips at interior sections and 222 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the Type 3-SA/SB Barrier satisfies MASH TL-4 loading criteria for interior and end sections.

While the capacity of the single slope barrier appeared to meet MASH TL-4 requirements, the capacity of the retaining wall with respect to the combination of the soil retention loads and the impact loading of the barrier is unknown. Valid comparison with similar full-scale crash tested systems was not available, and calculation methods for this configuration were not available, Further research would be needed to verify the capacity of the barrier attached to the retaining wall foundation. Overall Evaluation

Based on this evaluation of height, geometry, and strength, the Georgia Type 3-SA/SB Barrier section is believed to be crashworthy and in compliance with MASH TL-4. However, the adequacy of the retaining wall to resist impacts was not evaluated, and the MASH crashworthiness of the overall barrier system remains inconclusive. The evaluation is summarized in Table C.2-2.

Table C.2-2. Georgia Type 3-SA/SB Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	232 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	137 kips		
	Punching Shear	Interior	284 kips		
		End	222 kips		
	Anchorage	RC Retaining Wall		Inconclusive	Inconclusive
Overall MASH Evaluation				Inconclusive	Inconclusive

C.2.1 References

1. *Special Detail Concrete Median Barrier Types 3-SA and 3-SB*, Georgia Department of Transportation, Atlanta, GA, December, 2017.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
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7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

Appendix D. Illinois Permanent Concrete Barrier MASH Evaluations

D.1. MASH Equivalency of Illinois DOT 44-in. Double Face Concrete Median Barrier

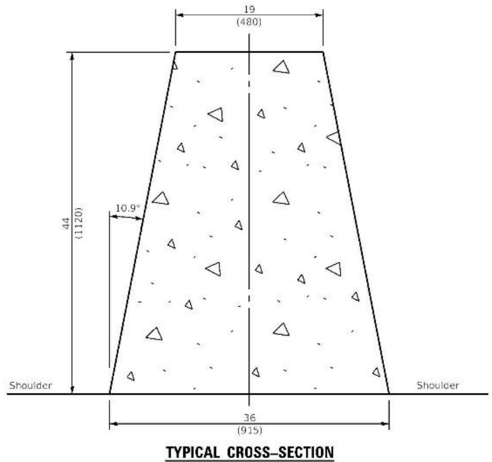


Figure D.1-1. Illinois DOT 44-in. Double Face Median Barrier Details [1]

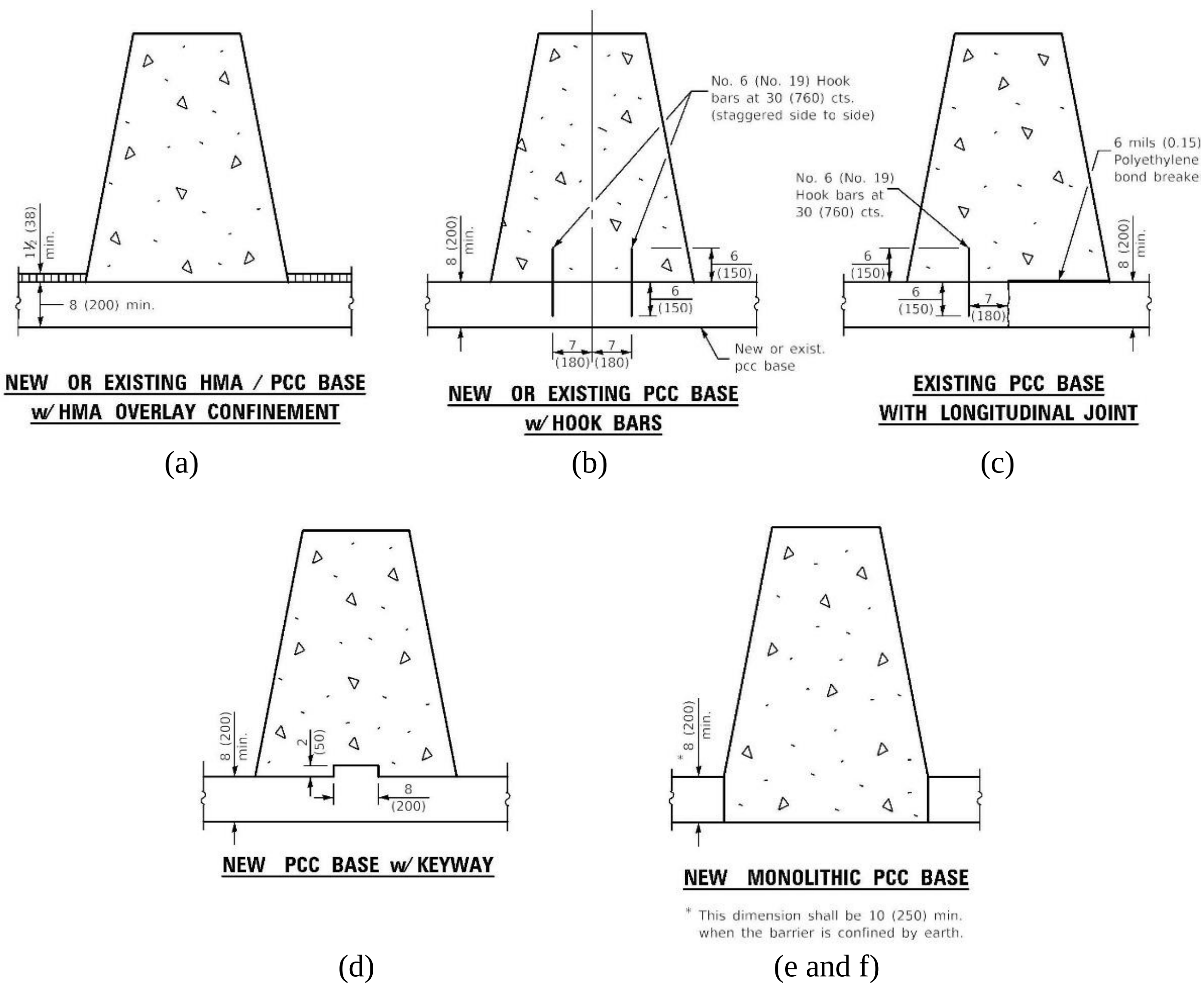


Figure D.1-2. Illinois DOT Double Face Median Barrier Anchorage Details [1]

Overview and Stability Evaluation

The Illinois DOT Double-Face Median Barrier is a 44-in. tall unreinforced concrete barrier with a 10.9-degree single-slope traffic face [1]. The top width of the barrier is 19 in., and the bottom width is 36 in. The barrier has six anchorage configurations: (a) 1½-in. asphalt keyway; (b) #6 reinforcing bars staggered at 30 in. on center; (c) 6 mils of bond breaker paired with #6 bars spaced at 30 in.; (d) a concrete base with 2-in. x 8 -in. vertical internal keyway; (e) 8-in. concrete keyway; and (f) 10-in. earthen keyway. Basic design details for the Double-Face Median Barrier are shown in Figure D.1-1, and the anchorage configurations are shown in Figure D.1-2.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and a strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain and redirect the 10000S test vehicle and prevent override [3–4]. Thus, the 44-in. tall Double-Face Median Barrier has the required height to contain and redirect the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic-side faces were sloped at 9 or 11 degrees, which are the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

The Double-Face Median Barrier is unreinforced, and therefore, the barrier was outside the scope of the conventional yield-line analysis presented in the AASHTO LRFD Bridge Design Specifications [9]. A punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications, with load requirements updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table D.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length.

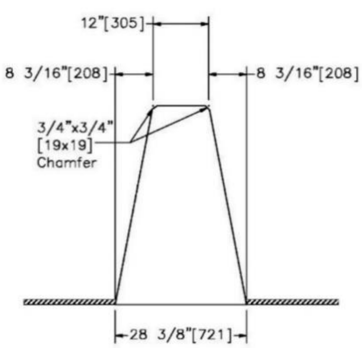
Table D.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

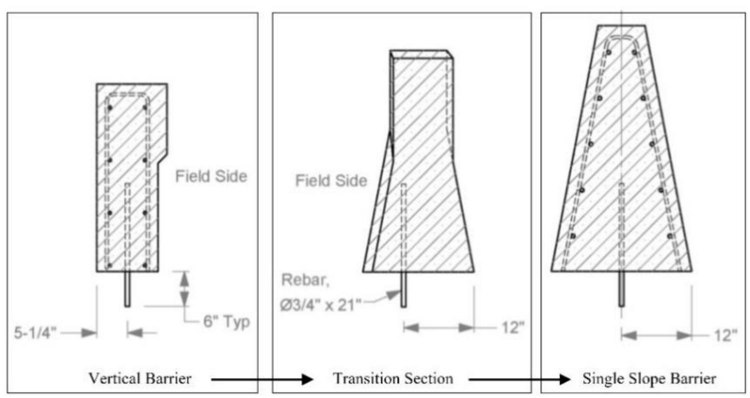
The punching shear capacity at the interior and end sections was 669 kips and 502 kips, respectively. These calculated capacities were greater than the required 80 kips, but because yield-line strength could not be calculated for the unreinforced barrier, analytical methods could not conclusively evaluate the barrier strength for MASH TL-4.

Direct Comparison of Strength and Anchorage

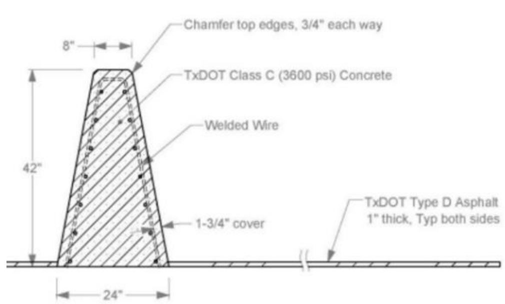
Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Double-Face Median Barrier. While no crash tests have been performed on barriers that are both unreinforced and anchored by dowels, an unreinforced single-slope concrete barrier with a 1-in. thick asphalt keyway on both sides of the barrier [6] and a reinforced concrete barrier anchored by dowels [10] have been crash tested in accordance with MASH TL-3. In addition, a reinforced single-single-slope concrete barrier with 1-in. asphalt keyway has been crash tested to MASH TL-4 [11]. The barrier profiles for the crash-tested systems are shown in Figure D.1-3.



Test No. OSSB-1



TxDOT T221 Transition



TxDOT 42-in. SSCB

Figure D.1-3. Test No. OSSB-1 [6], TxDOT T221 Transition (rebar hidden) [10], and TxDOT 42-in. SSCB Barrier Profiles [11]

In test no. OSSB-1 [6], a 42-in. tall, unreinforced, single-slope concrete barrier was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier. Anchorage was provided by a 1-in. thick asphalt keyway on each side of the barrier.

Crash testing has also been performed on a reinforced concrete barrier system anchored with dowel bars [10]. The TxDOT T221 transition barrier is a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall, vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21.

In a TL-4 evaluation, a TxDOT 42-in. SSCB anchored by a 1-in. asphalt keyway was crash tested in accordance with MASH test designation no. 4-12 [11]. The reinforced, single-slope concrete barrier contained and redirected the 10000S vehicle with minimal system deflections and barrier damage. A comparison of the crash tested systems with the Double-Face Median Barrier is provided in Table D.1-2.

Table D.1-2. Illinois Double-Face Median Barrier Anchorage Comparison

Evaluation Parameter		**OSSB-1 (TL-3)** ***[5]***	**TxDOT SSCB 469467-3-1 (TL-4)**	**TxDOT T221 469689-2-2 (TL-3)**	**Double-Face Median Barrier**	
Anchorage	Type	Asphalt Keyway	Asphalt Keyway	1 x #6 Dowels	1 x #6 Dowels	Keyway
	Depth	1 in.	1 in.	21-in. bar, Embed 6 in.	12-in. bar, Embed 6 in.	1½-in. Asphalt, 2” x8” Vertical Internal, 8-in. Concrete, & 10-in. Earthen
	Spacing	Continuous	Continuous	8 ft	30 in.	Continuous
Geometry	Base Width	28⅜ in.	24 in.	12 to 24 in.	36 in.	
	Top Width	12 in.	8 in.	8 to 10 in.	19 in.	
	Height	42 in.	42 in.	32 to 42 in.	44 in.	
Reinf.	Longitudinal (Horizontal)	--	14 x D18 WWR	10 x #5	--	
	Vertical	--	D9 WWR @ 8 in.	2 x #5 @ 12 in.	--	
Stability	Section Weight	904 plf	700 plf	540 plf	1,260 plf	
	Overturning Stability per ft	1,068 ft-lb	700 ft-lb	405 ft-lb	1,890 ft-lb	

The unreinforced barrier in test no. OSSB-1 provided a basis for strength evaluation of the unreinforced Double Face Median Barrier. The Double Face Median Barrier is of a similar height and several inches wider than the test no. OSSB-1 barrier and is expected to have equal or greater strength than the TL-3 crash tested barrier. The cross section of the median barrier is also significantly larger than the TL-4 crash tested TxDOT SSCB barrier. This increased size and section weight could also increase impact resistance. While this size and weight may suggest that the median barrier may be crashworthy to MASH TL-4, the unreinforced Double-Face Median Barrier cannot conclusively be justified as adequate for MASH TL-4 strength by direct comparison with the longitudinally and vertically reinforced TxDOT SSCB.

Test no. OSSB-1 also provides a basis for the TL-3 evaluation of several anchorage configurations used with the Double-Face Median Barrier. As part of the research associated with test no. OSSB-1, the 1-in. asphalt keyway was assessed as a critically weak, anchorage configuration as compared to other Ohio DOT anchorage options [6]. Therefore, the 1½-in. thick asphalt keyway configuration of the Double-Face Median Barrier is expected to have adequate strength to resist MASH TL-3 impacts. By extension, the 8-in. thick concrete keyway and 10-in. thick earthen keyway are also expected to have adequate strength to resist MASH TL-3 impacts.

Additional justification for the soil keyway came from test no. 405160-13-1, which was conducted on a reinforced-concrete, single-slope barrier positioned 24 in. away from a slope break point [5]. The base width was 24 in., and the overall height was 42 in. with the bottom 10 in. embedded in MASH standard soil. The barrier contained and redirected the 2270P vehicle and met all MASH evaluation criteria for test no. 3-11. While the 44-in. high, Double-Face Median Barrier is taller than the TTI crash-tested barrier [5], the comparable 10-in. thick earthen keyway and greater section weight of the Double-Face Median Barrier are expected to produce equal or greater anchorage capacity as compared to the TTI crash-tested barrier [5]. This comparison further justifies deeming the earthen keyway configuration to be crashworthy to MASH TL-3.

Given that the 1-in. thick asphalt keyway in test no. OSSB-1 was assessed as a critically weak anchorage configuration, the staggered #6 dowel bar anchorage used with the Double-Face Median Barrier is also anticipated to have strength equal to or greater than the crash-tested asphalt keyway. However, the TxDOT T221 transition provides additional information on dowel anchorage crashworthiness [10]. The TxDOT T221 transition was anchored by #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The dowel bar anchorage configuration of the Double-Face Median Barrier uses #6 dowel bars staggered at 30-in. intervals and embedded 6 in. The tighter spacing mean that per unit length, the Double-Face Median Barrier provides over three times the bar area of the TxDOT T221 transition. Therefore, the Double-Face Median Barrier is considered to have anchorage strength equal to or greater than the MASH TL-3 TxDOT T221 transition barrier [10].

Unfortunately, there is no known crash test data for unreinforced barriers that could justify the Double-Face Median Barrier crashworthiness when configured with the 2-in. x 8 in. vertical internal keyway or the bond breaker anchorage. Furthermore, while the strength of the #6 staggered dowel anchorage and the three keyway anchorage configurations were justified as adequate for MASH TL-3 impacts, there are no known TL-4 crash tests of similar systems. Thus, the MASH TL-4 evaluation of the Double-Face Median Barrier remains inconclusive until further testing or evaluation is conducted.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Double-Face Median Barrier is believed to be crashworthy and in compliance with MASH TL-3 for the following anchorage configurations: 1½-in. asphalt keyway; 8-in. concrete keyway; 10-in. earthen keyway; and #6 staggered dowel bars. The concrete base with vertical internal keyway and the #6 bars with bond breaker could not be evaluated by calculation or direct comparison. Some configurations of the barrier may be crashworthy to MASH TL-4 standards, but the strength and anchorage of the unreinforced barrier are difficult to justify as adequate to MASH TL-4 crashworthiness. The TL-4 evaluation of the barrier was, therefore, inconclusive for all anchorage configurations. The evaluation is summarized in Table D.1-3.

Table D.1-3. Illinois 44-in. Double Face Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 44 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="10">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>--</td><td rowspan="4">≥ 70 kips
Pass*</td><td rowspan="4">≥ 80 kips
Inconclusive</td></tr>
<tr><td>End</td><td>--</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>669 kips</td></tr>
<tr><td>End</td><td>502 kips</td></tr>
<tr><td rowspan="6">Anchorage</td><td colspan="2">PCC Base with 2-in. x 8-in. Vertical Internal Keyway</td><td>Inconclusive</td><td>Inconclusive</td></tr>
<tr><td colspan="2">8-in. Concrete Keyway</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="2">10-in. Earthen Keyway</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="2">1½-in. Asphalt Keyway</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Staggered #6 Dowel Bars @ 30 in.</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="2">#6 Dowel Bars @ 30 in. with Bond Breaker</td><td>Inconclusive</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass for Some Configurations</td><td>Inconclusive</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

D.1.1 References

1. Concrete Barrier, Double Face, 44 In. (1120 mm) Height, Standard 637006-04, Illinois Department of Transportation, January 1, 2019.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

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7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Bridge Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

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9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

10. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

11. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase I*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.

D.2. MASH Equivalency of the Illinois DOT 39-in. and 44-in. Constant Slope Concrete Parapets

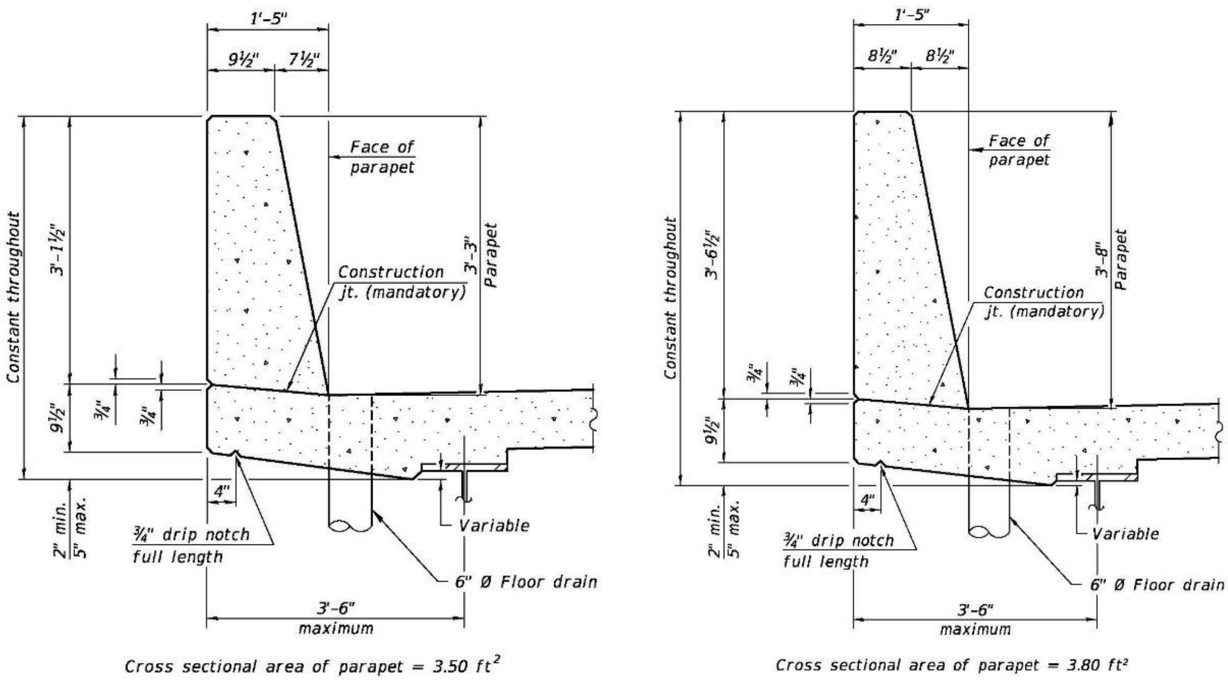

Figure D.2-1. Illinois DOT 39-in. and 44-in. Constant Slope Concrete Parapet Details [1]

Overview and Stability Evaluation

The Illinois DOT Constant Slope Concrete Parapets are 39-in. and 44-in. tall, reinforced half section concrete barriers with a 10.9-degree single-slope traffic face. The barriers are vertically reinforced with #5 stirrups spaced at 8 in. and embedded in the deck below. The 39-in. and 44-in. Constant Slope Parapet configurations are longitudinally reinforced with five and six #4 bars, respectively, on both the front and back sides of the barrier. Design details for the both the 39-in. and 44-in. Constant Slope Concrete Parapets are shown Figure D.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 39-in. and 44-in. Constant Slope Concrete Parapets have the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table D.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. The results of the yield line and punching shear analyses are summarized in Table D.2-2.

Table D.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Table D.2-2. Computational Analysis Results for the Constant Slope Concrete Parapet

Barrier Configuration	Yield Line Strength, kips		Punching Shear Strength, kips	
	Interior Sections	End Sections	Interior Sections	End Sections
39-in. Parapet	206	123	205	167
44-in. Parapet	221	121	217	173

All calculated capacities were greater than the required 80 kips, and therefore, the 39-in. and 44-in. Constant Slope Concrete Parapets satisfy MASH TL-4 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Illinois 39-in. and 44-in. Constant Slope Concrete Parapets are believed to be crashworthy and in compliance with MASH TL-4. The evaluations are summarized in Tables D.2-3 and D.2-4.

Table D.2-3. Illinois 39-in. Constant Slope Concrete Parapet Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 39 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	206 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	123 kips		
	Punching Shear	Interior	205 kips		
		End	167 kips		
	Anchorage	Reinforcement		Pass	Pass
Overall MASH Evaluation				Pass	Pass

Table D.2-4. Illinois 44-in. Constant Slope Concrete Parapet Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 44 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	221 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	121 kips		
	Punching Shear	Interior	217 kips		
		End	173 kips		
	Anchorage	Reinforcement		Pass	Pass
Overall MASH Evaluation				Pass	Pass

D.2.1 References

1. Puzey, D.C., Illinois Department of Transportation Memorandum: Constant-Slope Parapet Update, Illinois Department of Transportation, January 11, 2019.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.

7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.

9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

Appendix E. Indiana Permanent Concrete Barrier MASH Evaluations

E.1. MASH Equivalency of the Indiana DOT Type FC F-Shape Barrier

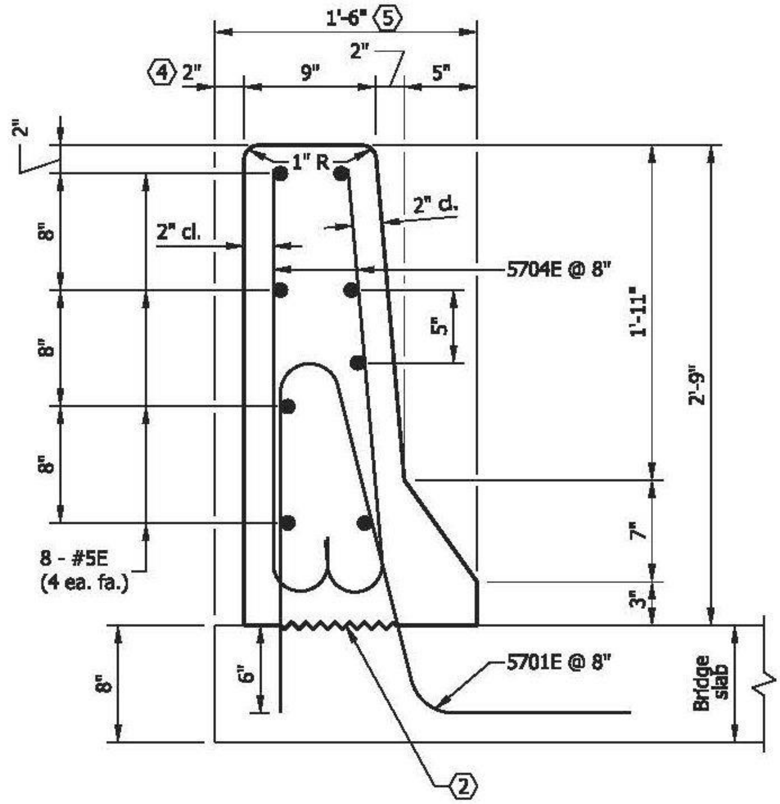

Figure E.1-1. Indiana DOT Type FC F-Shape Barrier Details [1]

Overview and Stability Evaluation

The Indiana DOT Type FC barrier is a 33-in. tall, F-shape reinforced concrete half-section barrier with a 9-in. top width. The barrier is vertically reinforced with #5 bars spaced at 8 in. Bent #5 bars, also spaced at 8 in., anchor the barrier to a concrete slab or bridge deck. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier. Design details for the Type FC barrier are shown in Figure E.1-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that TL-3 concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. However, F-shape barriers have not been tested at heights below 32 in., and therefore, 32 in. is considered the minimum TL-3 height requirement. Thus, the 33-in. tall Indiana DOT Type FC barrier has the required height to contain MASH TL-3 impact conditions.

Shape Evaluation

One MASH crash test has been conducted on a barrier with F-shape geometry. In test no. 469467-5-1, a 32-in. F-shape concrete barrier was successfully crash tested to MASH test designation no. 3-11 [4]. To date, MASH test designation no. 3-10 has not been conducted on a permanent F-shape barrier. However, a New Jersey barrier has been successfully crash tested to MASH test designation no. 3-10 [5], and F-shape barriers have been shown to induce less vehicle climb than New Jersey shape barriers due to the reduced toe section height in F-shape geometry. Therefore, it is believed that the F-shape geometry would perform similarly or better than the crashworthy New Jersey barrier. Additionally, vertical concrete barriers, which are known to produce the highest vehicle decelerations of the common concrete barrier shapes, have also been successfully crash tested to MASH test designation no. 3-10 [6]. Since the New Jersey and vertical barrier geometries have been successfully crash tested to MASH test designation no. 3-10, it is believed that an F-shape barrier would also be crashworthy [7]. Therefore, F-shape geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [8], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table E.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table E.1-1. Effective Loads for Design of MASH Barriers [9]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analyses were conducted for the full barrier section and the upper section of the barrier. The full section had a strength of 191 kips for interior sections and 99 kips for end sections adjacent to discontinuities (expansion gaps and joints). The upper section of the barrier had a strength of 242 kips for interior sections and 199 kips for and end sections. The punching shear capacity of the barrier was 152 kips at interior sections and 120 kips at end sections. All calculated capacities were greater than the required 70 kips, and therefore, the Type FC barrier satisfies the MASH TL-3 loading criteria for interior and end sections.

Overall Evaluation

Based on the evaluation of height, geometry, strength, and anchorage, the Indiana DOT Type FC F-shape Barrier is believed to be crashworthy to MASH TL-3. The evaluation is summarized in Table E.1-2.

Table E.1-2. Indiana Type FC Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 33 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">F-Shape</td><td>Pass</td><td rowspan="6">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>191 kips</td><td rowspan="4">≥ 70 kips
Pass</td></tr>
<tr><td>End</td><td>99 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>152 kips</td></tr>
<tr><td>End</td><td>120 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Pass</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Fail</td></tr>
</table>

E.1.1 References

1. Bridge Railing Type FC, Standard Drawing No. E 706-BRSF-01, Indiana Department of Transportation, September 4, 2012.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Silvestri-Dobrovolny, C., Schulz, N., Moran, S., Skinner, T., Bligh, R.P., and Williams, W., *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, National Cooperative Highway Research Program (NCHRP) Report No. 20-07(395), Texas Transportation Institute, College Station, TX, November 2017.
4. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase 1*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.
5. Polivka, K.A., et al., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier – Update to NCHRP 350 Test No. 3-10 (2214NJ-1)*, Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 2016.
6. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11*, Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.
7. NCHRP Web Only Document 157: Volume I: Evaluation of Existing Roadside Safety Hardware using Updated Criteria – Technical Report, Bullard, D.L., et al., Final Report for NCHRP Project 22-14(03), National Cooperative Highway Research Program, Transportation Research Board, March 2010.
8. *LRFD Bridge Design Specifications,* Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
9. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

E.2. MASH Equivalency of the Indiana DOT Type FT F-Shape Barrier

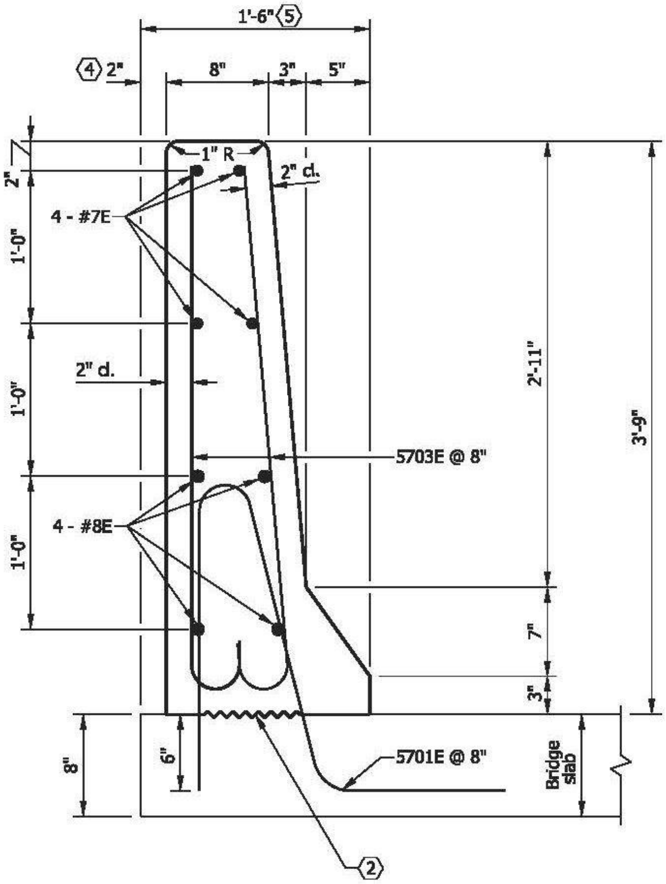

Figure E.2-1. Indiana DOT Type FT F-Shape Barrier Details [1]

Overview and Stability Evaluation

The Indiana DOT Type FT barrier is a 45-in. tall, F-shape reinforced concrete half-section barrier with an 8-in. top width. The barrier is vertically reinforced with #5 bars spaced at 8 in. Bent #5 bars, also spaced at 8 in., anchor the barrier to a concrete slab or bridge deck. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier. Design details for the Type FT barrier are shown in Figure E.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 45-in. tall Indiana DOT Type FT barrier has the required height to contain MASH TL-4 impact conditions.

Shape Evaluation

One MASH crash test has been conducted on a barrier with F-shape geometry. In test no. 469467-5-1, a 32-in. F-shape concrete barrier was successfully crash tested to MASH test designation no. 3-11 [5]. To date, MASH test designation no. 3-10 has not been conducted on a permanent F-shape barrier. However, a New Jersey barrier has been successfully crash tested to MASH test designation no. 3-10 [6], and F-shape barriers have been shown to induce less vehicle climb than New Jersey shape barriers due to the reduced toe section height in F-shape geometry. Therefore, it is believed that the F-shape geometry would perform similarly or better than the crashworthy New Jersey barrier. Additionally, vertical concrete barriers, which are known to produce the highest vehicle decelerations of the common concrete barrier shapes, have also been successfully crash tested to MASH test designation no. 3-10 [7]. Since the New Jersey and vertical barrier geometries have been successfully crash tested to MASH test designation no. 3-10, it is believed that an F-shape barrier would also be crashworthy [8]. Therefore, F-shape geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table E.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table E.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analyses were conducted for the full barrier section and the upper section of the barrier. The full section had a strength of 182 kips for interior sections and 98 kips for end sections adjacent to discontinuities (expansion gaps and joints). The upper section of the barrier had a strength of 200 kips for interior sections and 180 kips for end sections. The punching shear capacity of the barrier was 152 kips at interior sections and 120 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the Type FT barrier satisfies the MASH TL-4 loading criteria for interior and end sections.

Overall Evaluation

Based on the evaluation of height, geometry, strength, and anchorage, the Type FT barrier is believed to be crashworthy to MASH 2016 TL-4. The evaluation is summarized in Table E.2-2.

Table E.2-2. Indiana Type FT Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 45 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">F-Shape</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>182 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 80 kips
Pass</td></tr>
<tr><td>End</td><td>98 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>178 kips</td></tr>
<tr><td>End</td><td>140 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Pass</td><td>Pass</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Pass</td></tr>
</table>

E.2.1 References

1. Bridge Railing Type FT, Standard Drawing No. E 706-BRSF-02, Indiana Department of Transportation, September 4, 2012.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

5. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase 1*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.

6. Polivka, K.A., et al., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier – Update to NCHRP 350 Test No. 3-10 (2214NJ-1),* Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 2016.

7. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11,* Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.

8. NCHRP Web Only Document 157: Volume I: Evaluation of Existing Roadside Safety Hardware using Updated Criteria – Technical Report, Bullard, D.L., et al., Final Report for NCHRP Project 22-14(03), National Cooperative Highway Research Program, Transportation Research Board, March 2010.

9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

E.3. MASH Equivalency of the Indiana 45-in. Concrete Median Barrier

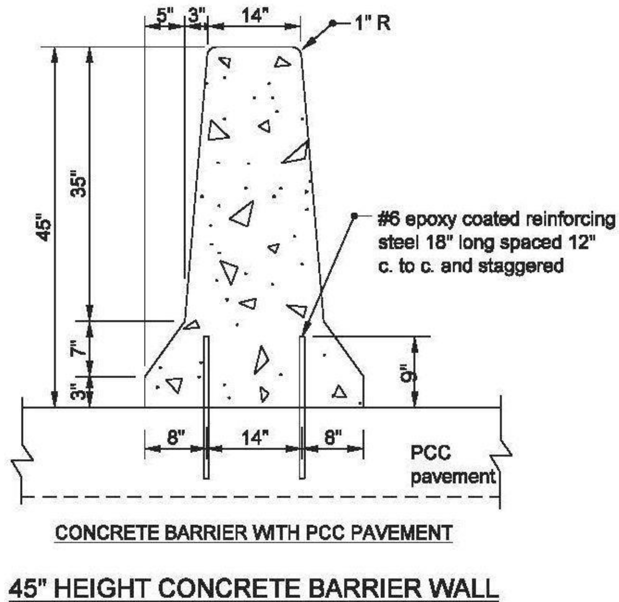

Figure E.3-1. Indiana DOT 45-in. Concrete Median Barrier Details [1]

Overview and Stability Evaluation

The Indiana DOT Concrete Median barrier is a 45-in. tall, F-shape unreinforced concrete barrier with a 14-in. top width. Anchorage is provided by embedded #6 reinforcing bars staggered at 12 in. on center. Design details for the 45-in. tall Concrete Median Barrier are shown in Figure E.3-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 45-in. tall Indiana DOT Concrete Median Barrier has the required height to contain MASH TL-4 impact conditions.

Shape Evaluation

One MASH crash test has been conducted on a barrier with F-shape geometry. In test no. 469467-5-1, a 32-in. F-shape concrete barrier was successfully crash tested to MASH test designation no. 3-11 [5]. To date, MASH test designation no. 3-10 has not been conducted on a permanent F-shape barrier. However, a New Jersey barrier has been successfully crash tested to MASH test designation no. 3-10 [6], and F-shape barriers have been shown to induce less vehicle climb than New Jersey shape barriers due to the reduced toe section height in F-shape geometry. Therefore, it is believed that the F-shape geometry would perform similarly or better than the crashworthy New Jersey barrier. Additionally, vertical concrete barriers, which are known to produce the highest vehicle decelerations of the common concrete barrier shapes, have also been successfully crash tested to MASH test designation no. 3-10 [7]. Since the New Jersey and Vertical barrier geometries have been successfully crash tested to MASH test designation no. 3-10, it is believed that an F-shape barrier would also be crashworthy. This conclusion is also supported in the NCHRP Web Only Document 157: Volume I: Evaluation of Existing Roadside Safety Hardware using Updated Criteria [8]. Therefore, F-shape geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Because the Concrete Median Barrier is unreinforced, the barrier was outside the scope of the conventional yield line analysis presented in the AASHTO LRFD Bridge Design Specifications [9]. A punching shear analysis for both interior and end sections could still be conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. Load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table E.3-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5 ft length.

Table E.3-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

The punching shear capacity at interior and end sections was 460 kips and 350 kips, respectively. These calculated capacities were greater than the required 80 kips, but because yield line strength could not be calculated for the unreinforced barrier, analytical methods could not conclusively evaluate the barrier strength for MASH TL-4.

Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Concrete Median Barrier. While no crash tests have been performed on barriers that are both unreinforced and anchored by dowels, an unreinforced single-slope concrete barrier with an asphalt keyway has been crash tested in accordance with MASH TL-3. In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [10]. The 42-in.

tall barrier featured a 10.9-degree slope, 12-in. top width, and 28-in. bottom width. Anchorage was provided by a 1-in. thick asphalt keyway, which researchers deemed a critically weak anchorage configuration. Therefore, dowel bar anchorages such as that used in the 45-in. Median Barrier would provide increased anchorage strength over the asphalt keyway used in test no. OSSB-1.

The F-shape Concrete Median Barrier is 2 in. wider than the single-slope barrier in test no. OSSB-1, and the increased base width and section weight act to increase overturning resistance. While the vehicle climb associated with impacts on F-shape barriers may increase the effective height of the impact force, this is balanced by an increased impulse time and a reduced impact force. Taken in conjunction with the increased anchorage strength provided by the dowel bars compared to the asphalt keyway in test no. OSSB-1, the Concrete Median Barrier is anticipated to have the necessary strength and anchorage for MASH TL-3 impact conditions.

There has been a TL-4 crash test of a 42-in. tall, reinforced, single-slope concrete barrier with 1-in. asphalt keyway [5]. While the height and cross-sectional area of the tested barrier were comparable to the Concrete Median Barrier, the unreinforced median barrier could not reasonably be compared with the longitudinally and vertically reinforced crash-tested barrier. There were no other known TL-4 crash tests of comparable barrier, and the TL-4 evaluation was, therefore, inconclusive.

Overall Evaluation

Based on the evaluation of height, geometry, strength, and anchorage, the Indiana 45-in. Concrete Median Barrier is believed to be crashworthy to MASH 2016 TL-3. The barrier may also be crashworthy to MASH TL-4 standards, but the strength and anchorage of the unreinforced barrier are difficult to qualify, and the TL-4 evaluation was inconclusive. The evaluation is summarized in Table E.3-2.

Table E.3-2. Indiana 45-in. Concrete Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 45 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">F-Shape</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>--</td><td rowspan="4">≥ 70 kips
Pass*</td><td rowspan="4">≥ 80 kips
Inconclusive</td></tr>
<tr><td>End</td><td>--</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>460 kips</td></tr>
<tr><td>End</td><td>350 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Dowel Bars</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

E.3.1 References

1. Concrete Barrier Details, Standard Drawing No. E 602-CCMB-04, Indiana Department of Transportation, September 1, 2006.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
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7. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11*, Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.
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Appendix F. Iowa Permanent Concrete Barrier MASH Evaluations

F.1. MASH Equivalency of the Iowa DOT 54-in. F-Shape Roadside Barrier

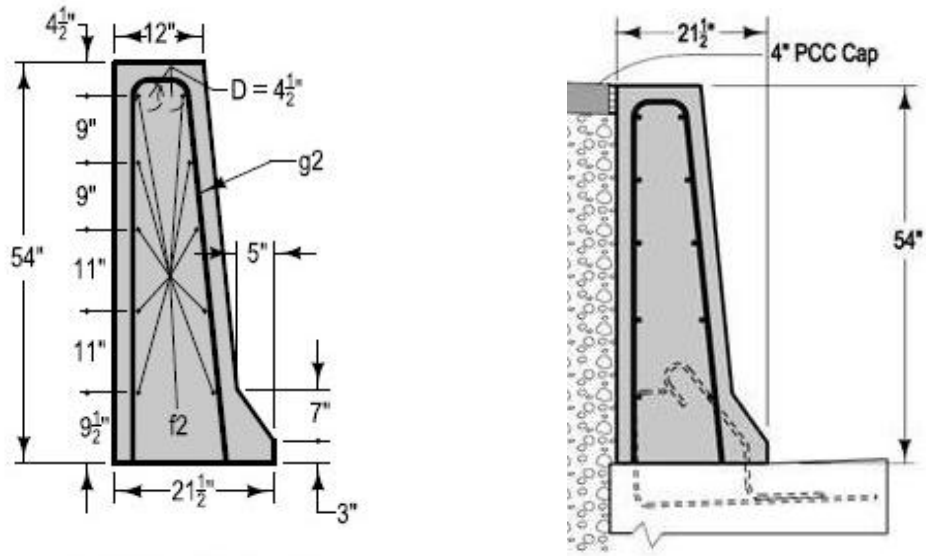

Figure F.1-1. Iowa DOT 54-in. F-Shape Roadside Barrier Details [1]

Overview and Stability Evaluation

The Iowa DOT F-shape Roadside Barrier is a 54-in. tall, F-shape reinforced concrete barrier with a 12-in. top width. The barrier is vertically reinforced with #6 stirrups spaced at 12-in., and is anchored to the deck with #5 bars, also spaced at 12 in. Longitudinal reinforcement consists of five #6 bars on both the front and back sides of the barrier. Design details for the F-shape Roadside Barrier are shown in Figure F.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 54-in. tall Iowa DOT F-shape Roadside Barrier has the required height to contain MASH TL-4 impact conditions.

Shape Evaluation

One MASH crash test has been conducted on a barrier with F-shape geometry. In test no. 469467-5-1, a 32-in. F-shape concrete barrier was successfully crash tested to MASH test designation no. 3-11 [5]. To date, MASH test designation no. 3-10 has not been conducted on a permanent F-shape barrier. However, a New Jersey barrier has been successfully crash tested to MASH test designation no. 3-10 [6], and F-shape barriers have been shown to induce less vehicle climb than New Jersey shape barriers due to the reduced toe section height in F-shape geometry. Therefore, it is believed that the F-shape geometry would perform similarly or better than the crashworthy New Jersey barrier. Additionally, vertical concrete barriers, which are known to produce the highest vehicle decelerations of the common concrete barrier shapes, have also been successfully crash tested to MASH test designation no. 3-10 [7]. Since the New Jersey and vertical barrier geometries have been successfully crash tested to MASH test designation no. 3-10, it is believed that an F-shape barrier would also be crashworthy [8]. Therefore, F-shape geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table F.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table F.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analyses were conducted for the full barrier section and the upper section of the barrier. The full section had a strength of 347 kips for interior sections and 157 kips for end sections adjacent to discontinuities (expansion gaps and joints). The upper section of the barrier had a strength of 415 kips for interior sections and 203 kips for end sections. The punching shear capacity of the barrier was 376 kips at interior sections and 277 kips at end sections. All capacities were greater than the required 80 kips, and therefore, the F-Shape Roadside Barrier satisfies MASH TL-4 loading criteria for interior and end sections.

Overall Evaluation

Based on the evaluation of height, geometry, strength, and anchorage, the Iowa F-Shape Roadside Barrier is believed to be crashworthy to MASH 2016 TL-4. The evaluation is summarized in Table F.1-2.

Table F.1-2. Iowa 54-in. F-Shape Roadside Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 54 in.		≥ 32 in. Pass	≥ 36 in. Pass
Shape		F-Shape		Pass	Pass
Strength	Yield Line	Interior	347 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	157 kips		
	Punching Shear	Interior	376 kips		
		End	277 kips		
	Anchorage	Reinforcement		Pass	Pass
Overall MASH Evaluation				Pass	Pass

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5. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase 1*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.
6. Polivka, K.A., et al., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier – Update to NCHRP 350 Test No. 3-10 (2214NJ-1),* Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 2016.
7. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11,* Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.
8. NCHRP Web Only Document 157: Volume I: Evaluation of Existing Roadside Safety Hardware using Updated Criteria – Technical Report, Bullard, D.L., et al., Final Report for NCHRP Project 22-14(03), National Cooperative Highway Research Program, Transportation Research Board, March 2010.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

F.2. MASH Equivalency of the Iowa DOT Vertical Bridge Railing

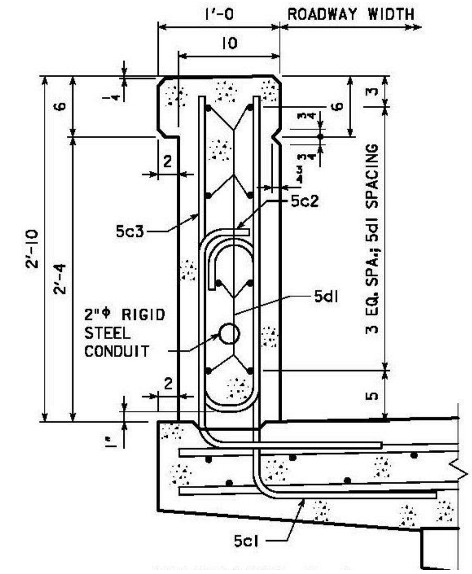

Figure F.2-1. Iowa DOT Vertical Bridge Railing Details [1]

Overview and Stability Evaluation

The Iowa DOT Vertical Bridge Railing is a 34-in. tall vertical face reinforced concrete barrier. The barrier is vertically reinforced with #5 stirrups spaced at 12-in. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier. Anchorage is provided by hooked #5 bars embedded in the deck and lapped with the vertical #5 stirrups. Design details for bridge railing are shown in Figure F.2-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. Thus, the 34-in. tall vertical bridge railing has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

Multiple full-scale MASH crash tests have been conducted on barriers with vertical traffic face geometry. Vertical-face concrete barriers with heights ranging from 32 in. to 34 in. have satisfied MASH safety performance criteria in tests with both small car and pickup truck vehicles [4–7]. Therefore, a vertical traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [8], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table F.2-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table F.2-1. Effective Loads for Design of MASH Barriers [9]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 148 kips for interior sections and 76 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 130 kips at interior sections and 122 kips at end sections. All capacities were greater than the required 70 kips, and therefore, the barrier satisfies MASH TL-3 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Iowa 34-in. Vertical Bridge Railing is believed to be crashworthy and in compliance with MASH TL-3. The evaluation is summarized in Table F.2-2.

Table F.2-2. Iowa Vertical Bridge Railing Evaluation Summary

<table>
<tr><th rowspan="2" colspan="2">Criteria</th><th rowspan="2" colspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 34 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Inconclusive</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Vertical</td><td>Pass</td><td rowspan="6">Not Evaluated due to Inconclusive Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>148 kips</td><td rowspan="4">≥ 70 kips
Pass</td></tr>
<tr><td>End</td><td>76 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>130 kips</td></tr>
<tr><td>End</td><td>122 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Pass</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

F.2.1 References

1. 232'-0 x 40'-0 Pretensioned Prestressed Concrete Beam Bridge Barrier Rail Details, Lee County, Design Sheet No. 23 of 28, File No. 29595, Design No. 910, Iowa Department of Transportation – Highway Division, February 2009.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
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4. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11*, Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.
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Appendix G. Kansas Permanent Concrete Barrier MASH Evaluations

G.1. MASH Equivalency of Kansas DOT Type II F-Shape Barrier

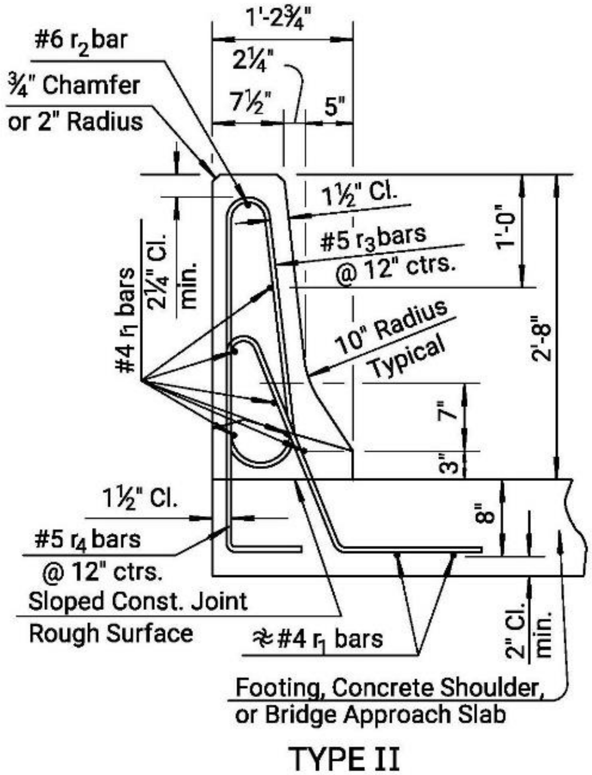

Figure G.1-1. Kansas DOT Type II F-Shape Barrier Details [1]

Overview and Stability Evaluation

The Kansas DOT Type II barrier is a 32-in. tall, F-shape reinforced concrete barrier with a 7½ in. top width. The barrier is vertically reinforced with #5 stirrups spaced at 12 in., and is anchored to the deck with bent #5 bars, also spaced at 12 in. Longitudinal reinforcement in the Type II barrier consists of one #6 bar and s #4 bars. Design details for the Type II barrier are shown in Figure G.1-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that TL-3 concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. However, F-shape barriers have not been tested at heights below 32 in., and therefore, 32 in. is considered the minimum TL-3 height requirement. Thus, the 32-in. tall Kansas DOT Type II barrier has the required height to contain MASH TL-3 impact conditions.

Shape Evaluation

One MASH crash test has been conducted on a barrier with F-shape geometry. In test no. 469467-5-1, a 32-in. F-shape concrete barrier was successfully crash tested to MASH test designation no. 3-11 [4]. To date, MASH test designation no. 3-10 has not been conducted on a permanent F-shape barrier. However, a New Jersey barrier has been successfully crash tested to MASH test designation no. 3-10 [5], and F-shape barriers have been shown to induce less vehicle climb than New Jersey shape barriers due to the reduced toe section height in F-shape geometry. Therefore, it is believed that the F-shape geometry would perform similarly or better than the crashworthy New Jersey barrier. Additionally, vertical concrete barriers, which are known to produce the highest vehicle decelerations of the common concrete barrier shapes, have also been successfully crash tested to MASH test designation no. 3-10 [6]. Since the New Jersey and vertical barrier geometries have been successfully crash tested to MASH test designation no. 3-10, it is believed that an F-shape barrier would also be crashworthy [7]. Therefore, F-shape geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [8], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table G.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table G.1-1. Effective Loads for Design of MASH Barriers [9]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analyses were conducted for the full barrier section and the upper section of the barrier. The full section had a strength of 100 kips for interior sections and 66 kips for end sections adjacent to discontinuities (expansion gaps and joints). Note that the end section capacity is less than the required 70 kips. The upper section had a strength of 116 kips for interior sections and 78 kips for end sections. The punching shear capacity of the barrier was 109 kips at interior sections and 88 kips at end sections. Therefore, the Type II Barrier satisfies MASH TL-3 loading criteria for interior sections but the capacity at end sections is insufficient.

Overall Evaluation

While the evaluation determined that barrier height and geometry met MASH TL-3 criteria, the computational evaluation of strength and anchorage indicated barrier end sections did not have adequate strength. Therefore, as summarized in Table G.1-2, the TL-3 evaluation of the barrier is inconclusive.

Table G.1-2. Kansas Type II Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 32 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">F-Shape</td><td>Pass</td><td rowspan="6">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>100 kips</td><td rowspan="4">≥ 70 kips
Inconclusive</td></tr>
<tr><td>End</td><td>66 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>109 kips</td></tr>
<tr><td>End</td><td>88 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Fail</td></tr>
</table>

G.1.1 References

1. Permanent Concrete Safety Barrier Type I, II, III, & IV (F-Shape), RD625, Kansas Department of Transportation, March 26, 2018.

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

3. Silvestri-Dobrovolny, C., Schulz, N., Moran, S., Skinner, T., Bligh, R.P., and Williams, W., *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, National Cooperative Highway Research Program (NCHRP) Report No. 20-07(395), Texas Transportation Institute, College Station, TX, November 2017.

4. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase 1*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.

5. Polivka, K.A., et al., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier – Update to NCHRP 350 Test No. 3-10 (2214NJ-1)*, Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 13, 2016.

6. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11*, Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.

7. NCHRP Web Only Document 157: Volume I: Evaluation of Existing Roadside Safety Hardware using Updated Criteria – Technical Report, Bullard, D.L., et al., Final Report for NCHRP Project 22-14(03), National Cooperative Highway Research Program, Transportation Research Board, March 2010.

8. *LRFD Bridge Design Specifications,* Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

9. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

G.2. MASH Equivalency of the Kansas DOT Type V Barrier

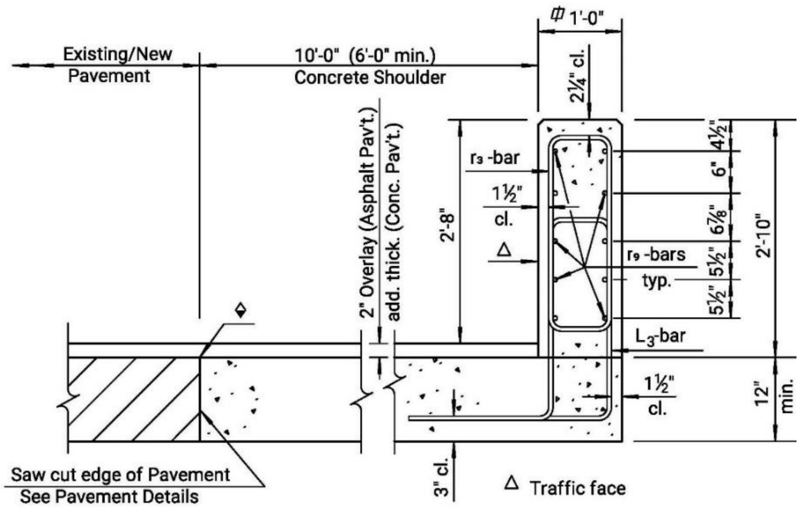

Figure G.2-1. Kansas DOT Type V Barrier Details [1]

Overview and Stability Evaluation

The Kansas DOT Type V Barrier is a 32-in. tall reinforced concrete barrier with a vertical traffic face. The barrier is vertically reinforced with #5 stirrups spaced at 12 in., and is anchored to the deck with bent #5 bars, also spaced at 12 in. Longitudinal reinforcement is provided by five #5 bars on both the front and back sides of the barrier. Design details for the Type V Barrier are shown in Figure G.2-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. The Type V barrier is 34 in. tall, but due to the specified 2-in. overlay, was considered 32 in. tall for the stability assessment. Thus, the 32-in. tall Kansas DOT Type V Barrier has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

Multiple full-scale MASH crash tests have been conducted on barriers with vertical traffic face geometry. Vertical-face concrete barriers with heights ranging from 32 in. to 34 in. have satisfied MASH safety performance criteria in tests with both small car and pickup truck vehicles [4–7]. Therefore, a vertical traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [8], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table G.2-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table G.2-1. Effective Loads for Design of MASH Barriers [9]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 181 kips for interior sections and 87 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 188 kips at interior sections and 143 kips at end sections. All capacities were greater than the required 70 kips, and therefore, the Type V barrier satisfies the MASH TL-3 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Kansas DOT Type V Barrier is believed to be crashworthy and in compliance with MASH TL-3. The evaluation is summarized in Table G.2-2.

Table G.2-2. Kansas Type V Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation TL-3	MASH Evaluation TL-4
Stability		Height = 32 in.		≥ 30 in. Pass	≥ 36 in. Fail
Shape		Vertical		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	181 kips	≥ 70 kips Pass	
		End	87 kips		
	Punching Shear	Interior	188 kips		
		End	143 kips		
	Anchorage	Reinforcement		Pass	
Overall MASH Evaluation				Pass	Fail

G.2.1 References

1. *Permanent Concrete Safety Barrier Type V, RD625C*, Kansas Department of Transportation, March 16, 2018.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Silvestri-Dobrovolny, C., Schulz, N., Moran, S., Skinner, T., Bligh, R.P., and Williams, W., *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, National Cooperative Highway Research Program (NCHRP) Report No. 20-07(395), Texas Transportation Institute, College Station, TX, November 2017.
4. Bielenberg, R.W., Yoo, S., Faller, R.K., Urbank, E.I., *Crash Testing and Evaluation of the HDOT 34-in. Tall Aesthetic Concrete Bridge Rail: MASH Test Designation Nos. 3-10 and 3-11*, Report No. TRP-03-420-19, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 21, 2019.
5. Whitesel, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 732SW Bridge Rail*, FHWA/CA15-2181, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, September 2016.
6. Williams, W.F., Bligh, R.P., Menges, W.L., *MASH Test 3-11 of the TxDOT T222 Bridge Rail*, FHWA/TX-14/9-1002-12-13, Texas Transportation Institute, College Station, TX, July 2016.
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9. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

Appendix H. Minnesota Permanent Concrete Barrier MASH Evaluations

H.1. MASH Equivalency of Minnesota DOT Type 36A/42A/54A Single-Slope Barriers

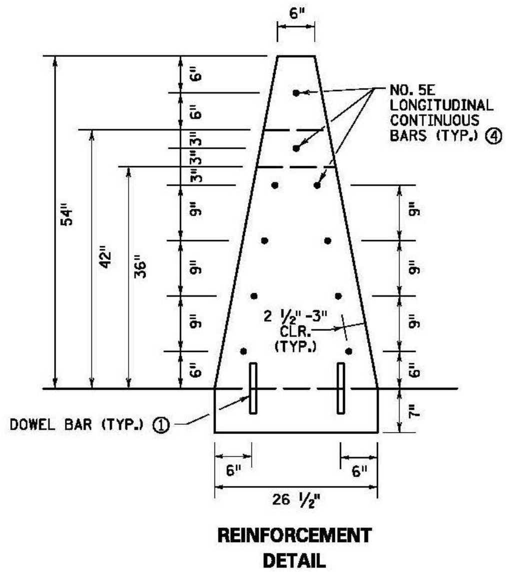


Figure H.1-1. Minnesota DOT Type 36A/42A/54A Single-Slope Barriers [1]

Overview and Stability Evaluation

The Minnesota Type 36A/42A/54A Single-Slope Barriers are 36-in., 42-in., and 54-in. tall barriers, respectively, with a 10.8-degree single-slope traffic face. The barrier end sections are vertically reinforced with #4 stirrups spaced at 6-in. No vertical reinforcement is provided at interior sections for any of the barrier configurations. All three barrier configurations are longitudinally reinforced with four #5 bars along both the front and back sides of the barrier. The Type 42A barrier incorporates one additional longitudinal #5 bar at top of the section, and the Type 54A incorporates two additional #5 bars. Anchorage is provided by a 10-in. deep by 10-ft long footing at the end sections. Additionally, the interior sections are anchored to a 7-in. deep footing by two #8 dowel bars spaced longitudinally at 24 in. Design details for the Single-Slope Barriers are shown in Figure H.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the Type 36A/42A/54A barriers have the required height to contain the single-unit truck under MASH TL-4 impact conditions.

<u>Shape Evaluation</u>

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

<u>Strength and Anchorage Evaluation</u>

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table H.1-1, the design load for a TL-4 barrier with a height of 36 in. is 70 kips distributed over a length of 4 ft, while the design load for a TL-4 barrier taller than 36 in. is 80 kips distributed over a 5-ft length. Due to the absence of vertical reinforcement at interior sections of the Type 36A/42A/54A barriers, the yield line analysis was limited to the end sections. Additionally, a punching shear analysis of interior and end sections was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications, and included the resistance of both concrete and vertical reinforcement. The results of the computational analysis are summarized in Table H.1-2.

Table H.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Table H.1-2. Computational Analysis Results for Type 36A/42A/54A Barriers

Barrier	Design Load	Yield Line Analysis		Punching Shear Analysis	
		Interior Section	End Section	Interior Section	End Section
36A	70 kips	*	135	272	214
42A	80 kips	*	127	255	210
54A	80 kips	*	139	340	271

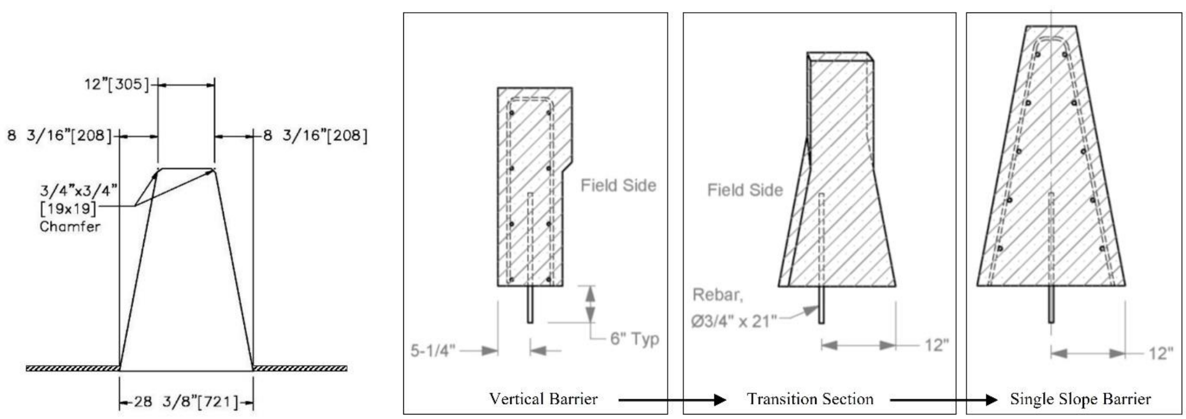
* Yield line analysis could not be conducted at the vertically unreinforced interior sections.

The calculated punching shear capacities for all three barriers were greater than the relevant design load. However, yield line strength of the vertically unreinforced interior sections could not be calculated, and therefore, analytical methods could not conclusively evaluate the barrier strength for MASH TL-4.

Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Type 36A/42A/54A barriers. Currently, no crash tests have been performed on barriers with only longitudinal reinforcement. However, an unreinforced single-slope barrier has been crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. The unreinforced barrier was anchored with a 1-in. thick asphalt keyway, which researchers deemed a critically weak anchorage configuration. Therefore, dowel bar anchorage, such as that used in the Type 36A, 42A, and 54A would provide increased anchorage strength over the asphalt keyway used in test no. OSSB-1.

Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. The transition was anchored by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety criteria of MASH test designation no. 3-21 [10]. The profiles of the two crash tested systems are shown in Figure H.1-2 and a comparison with the Type 36A, 42A, and 54A barriers is provided in Table H.1-3.



Test No. OSSB-1 TxDOT T221 Transition

Figure H.1-2. Test No. OSSB-1 Barrier [6] and TxDOT T221 Transition Barrier [10] Profiles

Table H.1-3. Minnesota Type 36A, 42A and 54A Anchorage Comparison

Evaluation Parameter		**OSSB-1 (TL-3)**	**TxDOT T221 469689-2-2 (TL-3)** [(a)]	**Minnesota DOT Single-Slope Barriers**		
				36A	**42A**	**54A**
Barrier Shape		Single-Slope	Transition: Single-Slope and Vertical	Single-Slope		
Anchorage	Type	Asphalt Keyway	1 x #6 Dowels	2 x #8 Dowels		
	Depth	1 in.	21 in. bar (Embed 6 in.)	8 in. bar (Embed 4 in.)		
	Spacing	Continuous	8 ft	2 ft		
Geometry	Base Width	28⅜ in.	18 in.	24 in.		
	Top Width	12 in.	10 in.	10 in.	8 in.	6 in.
	Height	43 in.	37 in.	36 in.	42 in.	54 in.
Reinf.	Longitudinal	--	10 x #5	8 x #5	9 x #5	10 x #5
	Vertical	--	2 x #5 @ 12 in.	--	--	--
Stability	Section Weight	904 plf	540 plf	637 plf	700 plf	844 plf
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	637 ft-lb	700 ft-lb	844 ft-lb

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

Compared to the test no. OSSB-1 barrier, the Minnesota DOT barriers had similar overall geometry, but were 4 in. narrower at the base. However, the #5 longitudinal reinforcement in the Minnesota DOT barriers would provide additional strength compared to the unreinforced barrier. Therefore, the Type 36A, 42A, and 54A barriers were considered to have strengths equal to or greater than the unreinforced MASH TL-3 barrier evaluated in test no OSSB-1.

As shown in Table H.1-3, the TxDOT T221 transition was anchored by #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The Minnesota DOT barriers were anchored by two #8 dowel bars spaced at 2-ft intervals, and a 4-in. embedment depth. Although the Minnesota DOT barrier dowels had a reduced embedment depth, the larger bar size and tighter spacing mean that per unit length, the Minnesota DOT barriers provide fourteen times the dowel bar area of the TxDOT T221 transition. Therefore, the Type 36A, 42A, and 54A barriers were considered to have anchorage strengths equal to or greater than the MASH TL-3 TxDOT T221 transition barrier.

Unfortunately, while the systems in test nos. OSSB-1 and 469689-2-2 provided information on the crashworthiness of unreinforced barriers and dowel-bar anchorages, the systems were only evaluated to MASH TL-3 criteria. Crash testing of similar MASH TL-4 barriers could not be found. Thus, the MASH TL-4 evaluations of the Type 36A, 42A, and 54A barriers remain inconclusive until further testing or evaluation is conducted.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Minnesota Type 36A/42A/54A barriers are believed to be crashworthy and in compliance with MASH TL-3. The barriers may also be crashworthy and in compliance with MASH TL-4, but the absence of vertical reinforcement makes it difficult to qualify barrier strength and anchorage, and the MASH TL-4 evaluation was inconclusive. The barrier evaluations are summarized in Tables H.1-4 through H.1-6.

Table H.1-4. Minnesota Type 36A Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 36 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 70 kips Inconclusive
		End	135 kips		
	Punching Shear	Interior	272 kips		
		End	255 kips		
	Anchorage	Doweled Footing with End Anchorage		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

Table H.1-5. Minnesota Type 42A Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	127 kips		
	Punching Shear	Interior	255 kips		
		End	210 kips		
	Anchorage	Doweled Footing with End Anchorage		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

Table H.1-6. Minnesota Type 54A Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	**TL-4**
Stability		Height = 54 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	139 kips		
	Punching Shear	Interior	340 kips		
		End	271 kips		
	Anchorage	Doweled Footing with End Anchorage		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

H.1.1 References

1. Concrete Median Barrier Single Slope Type 36A, 42A, and 54A, Standard Plan 5-297.681 Minnesota Department of Transportation, August 10, 2016.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.
6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.
7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
10. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

Appendix I. Missouri Permanent Concrete Barrier MASH Evaluations

I.1. MASH Equivalency of Missouri DOT Type C Median Barrier

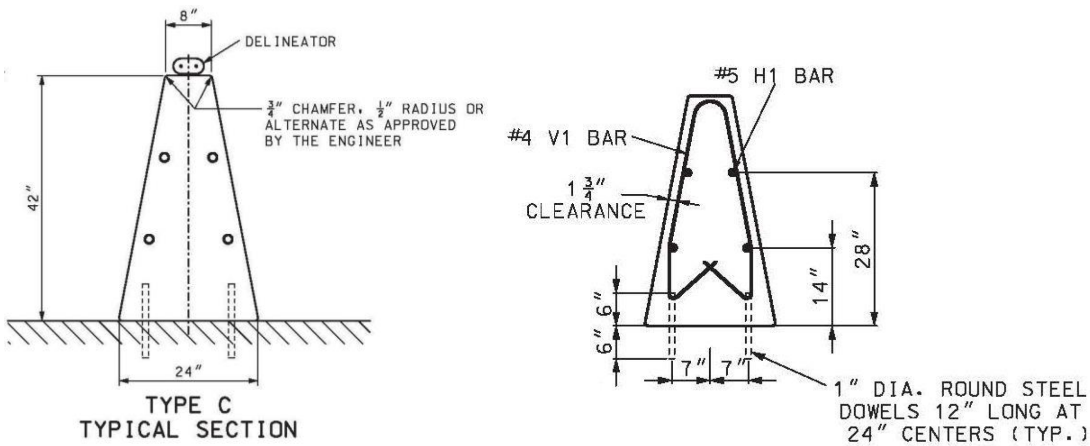


Figure I.1-1. Type C Median Barrier Details [1]

Overview and Stability Evaluation

The Missouri DOT Type C Median Barrier is a 42-in. tall concrete barrier with a 10.8-degree single-slope traffic face, 8-in. top width, and 24-in. bottom width. At end sections, the barrier is vertically reinforced with #4 bars at spacings of 4-in. to 12-in. on center. No vertical reinforcement is provided at interior sections. Longitudinal reinforcement is provided by two #5 bars on both the front and back sides of the barrier. The primary anchorage configuration utilizes two 1-in. diameter dowels spaced longitudinally at 24 in. However, the standard plans denote alternate anchorages of a 1¾-in. asphalt keyway or #8 bars with an epoxy anchor system. Basic design details for the Type C Median Barrier are shown in Figure I.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall Type C Median Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no.

3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table I.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Due to the absence of vertical reinforcement at interior sections, yield line analysis was limited to end sections. Both interior and end sections were analyzed for punching shear strength in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table I.1-1. Effective Loads for Design of MASH Barriers [3]

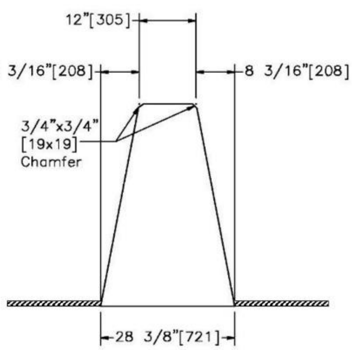
Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line strength of the end sections was 73 kips. The punching shear strength was 269 kips at interior sections and 220 kips at end sections. While the calculated punching shear capacities were greater than the required 80 kips, the calculated yield line strength at end sections was inadequate and yield line strength of the vertically unreinforced interior sections could not be calculated. Thus, analytical methods could not conclusively evaluate barrier strength for MASH TL-4.

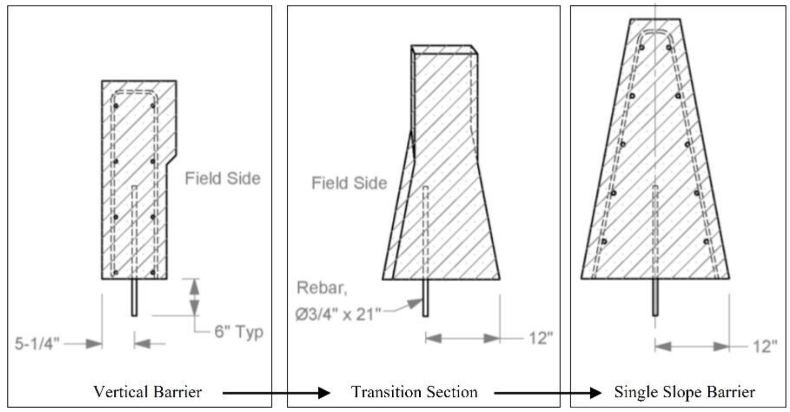
Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Type C Median Barrier. Currently, no MASH crash tests have been performed on barriers with only longitudinal reinforcement. However, an unreinforced single-slope barrier with asphalt keyway anchorage [6] and a concrete barrier with dowel anchorage [10] have been crash tested to MASH TL-3.

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier is a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [10]. The profiles of the crash tested systems are shown in Figure I.1-2 and a comparison with the Type C Median Barrier is provided in Table I.1-2.



Test No. OSSB-1



TxDOT T221 Transition

Figure I.1-2. Test No. OSSB-1 Barrier [6] and TxDOT T221 Transition Barrier [10] Profiles

Table I.1-2. Missouri Type C Anchorage Comparison

Evaluation Parameter		**OSSB-1 (TL-3)**	**TxDOT T221 [(a)] 469689-2-2 (TL-3)**	**MO Type C Median Barrier**	
Anchorage	Type	Asphalt Keyway	#6 Dowels	2 x 1-in. Dowels [(b)]	Asphalt Keyway
	Depth	1 in.	21 in. bar (Embed 6 in.)	12 in. bar (Embed 6 in.)	1¾ in.
	Spacing	Continuous	8 ft	2 ft	Continuous
Geometry	Base Width	28⅜ in.	18 in.	24 in.	
	Top Width	12 in.	10 in.	8 in.	
	Height	43 in.	37 in.	42 in.	
Reinforcement	Longitudinal	--	10 x #5	4 x #5	
	Vertical	--	2 x #5 @ 12 in.	--	
Stability	Section Weight	904 plf	540 plf	700 plf	
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	700 ft-lb	

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.
(b) Per Missouri standard plans, #8 epoxied bars may be substituted for the smooth 1-in. diameter dowels. For purposes of the MASH Evaluation, these anchorages were considered structurally equivalent.

Compared to the test no. OSSB-1 barrier, the Missouri Type C Median Barrier had similar overall geometry but was 4 in. narrower. However, the #5 longitudinal reinforcement in the Type C would provide increased strength compared to the unreinforced barrier. Therefore, the Type C Median Barrier was considered to have a strength equal to or greater than the unreinforced MASH TL-3 barrier evaluated in test no. OSSB-1. Additionally, as part of the research associated with test no. OSSB-1, the 1-in. asphalt keyway anchorage was deemed a critically weak anchorage configuration. Therefore, both the 1¾-in asphalt keyway anchorage and dowel bar anchorage used in the Type C Median Barrier would provide increased anchorage strength over the asphalt keyway used in test no. OSSB-1.

The TxDOT T221 transition was anchored by #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The Type C barrier uses two 1-in. dowels or two #8 bars spaced at 2-ft intervals and embedded 6 in. The larger bar size and tighter spacing mean that per unit length, the Type C barrier provides fourteen times the bar area of the TxDOT T221 transition. Therefore, the Type C Median Barrier is considered to have anchorage strength equal to or greater than the MASH TL-3 TxDOT T221 transition barrier.

Unfortunately, the test no. OSSB-1 and TxDOT T221 transition barrier systems were only evaluated to MASH TL-3 criteria and there are no known TL-4 crash test of similar systems. Thus, the MASH TL-4 evaluation of the Type C Median Barrier remains inconclusive until further testing or evaluation is conducted.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage the Type C Median Barrier is believed to be crashworthy and in compliance with MASH TL-3 when anchored with the specified 1-in. dowels, #8 epoxy rebar, or 1¾-in. asphalt keyway anchorages. The barrier may also be crashworthy and in compliance with MASH TL-4, but the absence of vertical reinforcement makes it difficult to qualify barrier strength and anchorage, and the TL-4 evaluation was inconclusive. The evaluation is summarized in Table I.1-3.

Table I.1-3. Missouri Type C Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	TL-4
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	73 kips		
	Punching Shear	Interior	269 kips		
		End	220 kips		
	Anchorage	1-in. Dowels or #8 Rebar		Pass*	Inconclusive
		1¾-in. Asphalt Keyway		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

I.1.1 References

1. *Permanent Concrete Traffic Barrier Type C, 617.10L, Sheet No. 4 of 11*, Missouri Highways and Transportation Commission, Jefferson City, MO, October 17, 2018.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
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10. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

Appendix J. Nebraska Permanent Concrete Barrier MASH Evaluations

J.1. MASH Equivalency of the Nebraska DOT 34 in. Median Barrier

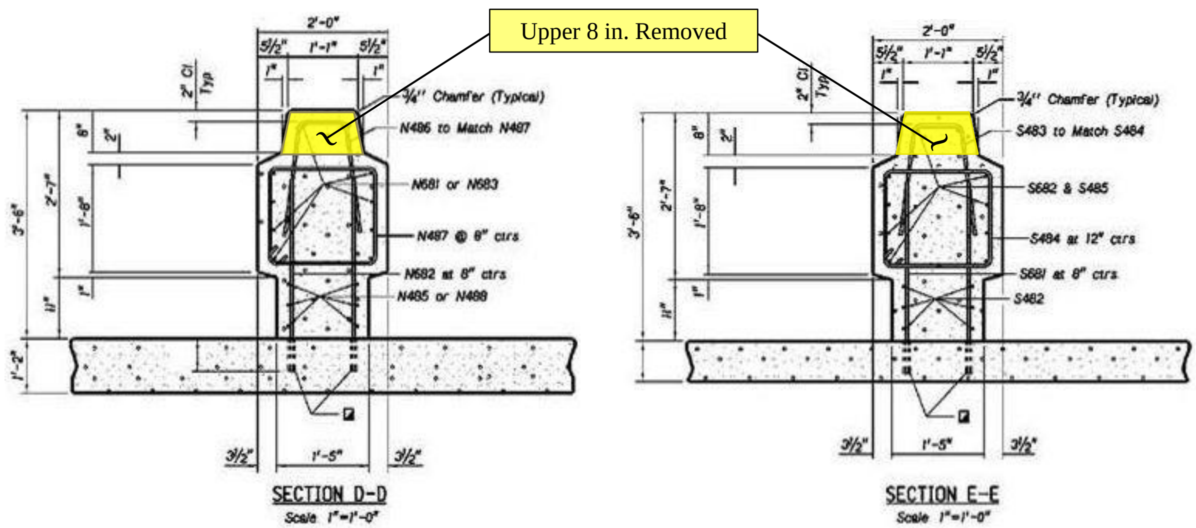

Figure J.1-1. Nebraska DOT 34-in. Median Barrier Design Details [1]

Overview and Stability Evaluation

The Nebraska DOT Median Barrier is a 34-in. tall reinforced concrete barrier with an aesthetic traffic face geometry. The barrier is vertically reinforced with a combination of #4 closed stirrups spaced at a maximum of 12 in. and #6 straight bars spaced at 8 in. along both the front and back sides of the barrier. Longitudinal reinforcement is provided by four #6 bars and three #4 bars on both the front and back sides of the barrier. Anchorage is provided by extending the vertical #6 bars into the deck below. The original design details shown in Figure J.1-1 are for a 42-in. concrete barrier. For the 34-in. configuration under evaluation, the upper 8 in. of the barrier are removed.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. Thus, the 34-in. tall Median Barrier has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

Although the traffic face of the Nebraska 34-in. Median Barrier has not been crash tested under MASH, MASH test designation nos. 3-10 and 3-11 have been conducted on post-and-beam barriers with similar details to the Median Barrier [7–8]. A 32-in. tall concrete post-and-beam barrier with a 19-in. contact width and 4½-in. post setback contained and redirected the small car. A 42-in. tall concrete post-and-beam barrier with a 21-in. contact width, trapezoidal post geometry, and no post setback contained and redirected both the small car and the pickup truck. The 34-in. tall Nebraska Median Barrier has a contact width of 20 in., intermediate of the two crashworthy post-and-beam systems. The median barrier is a solid concrete rail, and snag potential is expected to be eliminated as compared to the post-and-beam systems. Therefore, it is believed that the face shape of the Nebraska 34-in. Median Barrier would possess the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table J.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table J.1-1. Effective Loads for Design of MASH Barriers [10]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analyses were performed for the full section of the Median Barrier and the upper portion of the barrier. For the full section, barrier strength was 320 kips for interior sections and 127 kips for end sections adjacent to discontinuities (expansion gaps and joints). For the upper portion of the barrier, the strength was 413 kips for interior sections and 193 kips for end sections. The punching shear capacity of the full barrier section was 537 kips at interior sections and 379 kips at end sections. All calculated capacities were greater than the required 70 kips, and therefore, the Median Barrier satisfies MASH TL-3 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Nebraska 34-in. Median Barrier is believed to be crashworthy and in compliance with MASH TL-3. The evaluation is summarized in Table J.1-2.

Table J.1-2. Nebraska 34-in. Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 34 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Inconclusive</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Other</td><td>Pass</td><td rowspan="6">Not Evaluated due to Inconclusive Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>320 kips</td><td rowspan="4">≥ 70 kips
Pass</td></tr>
<tr><td>End</td><td>127 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>413 kips</td></tr>
<tr><td>End</td><td>193 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Pass</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

J.1.1 References

1. *Median Barrier Details*, State of Nebraska Department of Roads – Bridge Division, 2013.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Silvestri-Dobrovolny, C., Schulz, N., Moran, S., Skinner, T., Bligh, R.P., and Williams, W., *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, National Cooperative Highway Research Program (NCHRP) Report No. 20-07(395), Texas Transportation Institute, College Station, TX, November 2017.
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5. Williams, W.F., Bligh, R.P., Menges, W.L., *MASH Test 3-11 of the TxDOT T222 Bridge Rail*, FHWA/TX-14/9-1002-12-13, Texas Transportation Institute, College Station, TX, July 2016.
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7. Arrington, D.R., Bligh, R.P., Menges, W.L., *MASH Test 3-11 on the 5-Inch Cast in Place Deck Barrier Anchors*, FHWA/TX-12/9-1002-7, Texas Transportation Institute, College Station, TX, December 2011.
8. Williams, W.F., Bligh, R.P., Menges, W.L., Kuhn, D.L., *Crash Test and Evaluation of the TxDOT T224 Bridge Rail*, FHWA/TX-15/9-1002-15-5, Texas Transportation Institute, College Station, TX, January 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
10. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

J.2. MASH Equivalency of Nebraska DOT 42-in. Median Barrier

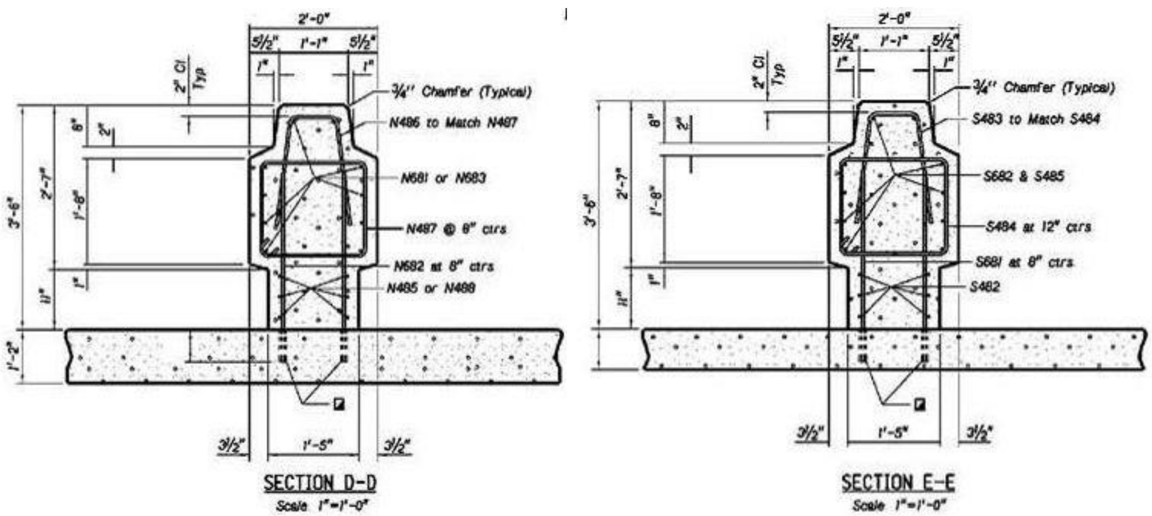

Figure J.2-1. Nebraska DOT 42-in. Median Barrier Design Details [1]

Overview and Stability Evaluation

The Nebraska DOT Median Barrier is a 42-in. tall reinforced concrete barrier with an aesthetic traffic face geometry. The barrier is vertically reinforced with a combination of #4 closed stirrups spaced at a maximum of 12 in. and #6 straight bars spaced at 8 in. along both the front and back sides of the barrier. Longitudinal reinforcement is provided by four #6 bars and four #4 bars on both the front and back sides of the barrier. Anchorage is provided by extending the vertical #6 bars into the deck below. Design details for the 42-in. Median Barrier are shown in Figure J.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall Median Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Although the traffic face of the Nebraska 34-in. Median Barrier has not been crash tested under MASH, MASH test designation nos. 3-10 and 3-11 have been conducted on post-and-beam barriers with similar details to the Median Barrier [5–6]. A 32-in. tall concrete post-and-beam barrier with a 19-in. contact width and 4½-in. post setback successfully contained and redirected the small car. A 42-in. tall concrete post-and-beam barrier with a 21-in. contact width, trapezoidal post geometry, and no post setback successfully contained and redirected both the small car and the pickup truck. The 34-in. tall Nebraska Median Barrier has a contact width of 20 in., intermediate of the two crashworthy post-and-beam systems. The median barrier is a solid concrete rail, and snag potential is expected to be eliminated as compared to the post-and-beam systems. The reduction in width that occurs in the upper 8 in. of the barrier is not expected to adversely impact safety performance. Therefore, it is believed that the face shape of the Nebraska 34-in. Median Barrier would possess the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [7], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table J.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table J.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analyses were conducted for the full barrier section and the upper portion of the barrier. For the full section, the yield line strength was 266 kips for interior sections and 163 kips for end sections adjacent to discontinuities (expansion gaps and joints). For the upper portion, the yield line strength was 337 kips for interior sections and 218 kips for end sections. The punching shear capacity of the full barrier section was 469 kips at interior sections and 348 kips at end sections. All calculated capacities were greater than the required 80 kips, and therefore, the 42-in. tall barrier satisfies MASH TL-4 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Nebraska 42-in. Median Barrier is believed to be crashworthy and in compliance with MASH TL-4. The evaluation is summarized in Table J.2-2.

Table J.2-2. Nebraska 42-in. Median Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation TL-3**	**MASH Evaluation TL-4**
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Other		Pass	Pass
Strength	Yield Line	Interior	266 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	163 kips		
	Punching Shear	Interior	469 kips		
		End	348 kips		
	Anchorage	Reinforcement		Pass	Pass
Overall MASH Evaluation				Pass	Pass

J.2.1 References

1. *Median Barrier Details,* State of Nebraska Department of Roads – Bridge Division, 2013.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
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6. Williams, W.F., Bligh, R.P., Menges, W.L., Kuhn, D.L., *Crash Test and Evaluation of the TxDOT T224 Bridge Rail*, FHWA/TX-15/9-1002-15-5, Texas Transportation Institute, College Station, TX, January 2018.
7. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

Appendix K. New Jersey Permanent Concrete Barrier MASH Evaluations

K.1. MASH Equivalency of the New Jersey DOT 34-in. Barrier Curb

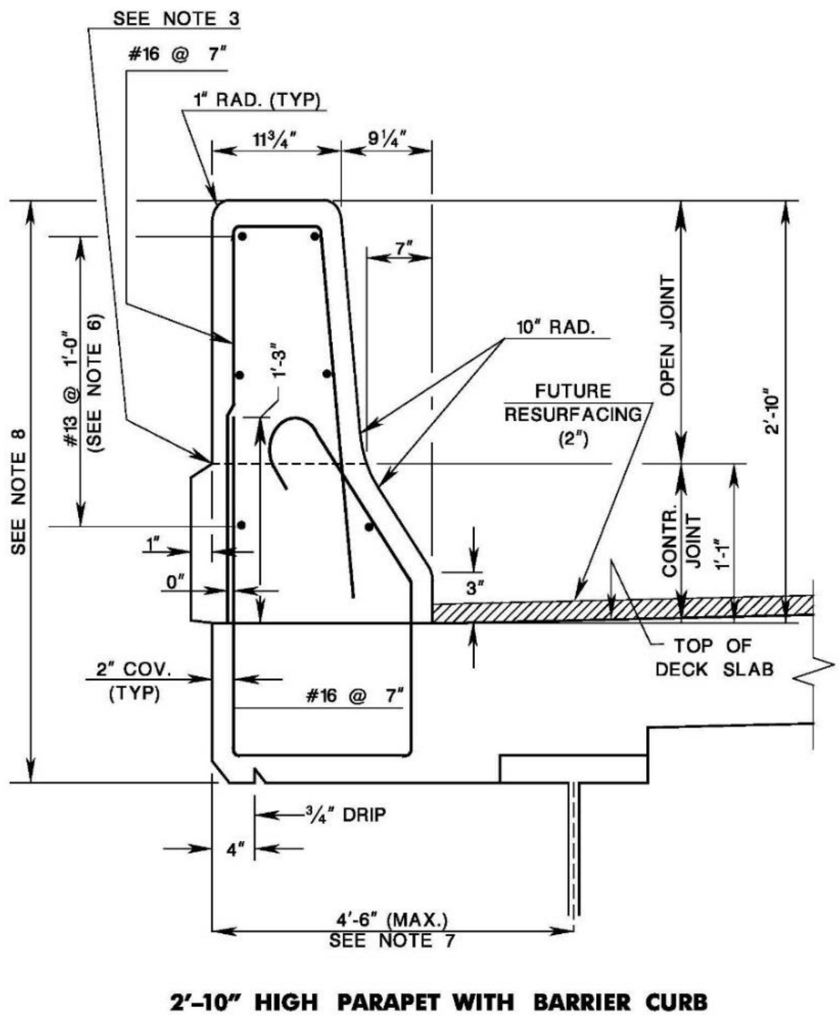


Figure K.1-1. New Jersey DOT 34-in. Barrier Curb [1]

Overview and Stability Evaluation

The New Jersey DOT Barrier Curb is a 34-in. tall, New Jersey shape reinforced concrete barrier with an 11¾ in. top width. The barrier is vertically reinforced with #5 bars at 7-in. spacing and is anchored to a concrete slab or bridge deck with a #5 bent bar, also spaced longitudinally at 7 in. Longitudinal reinforcement is provided by three #4 bars on both the front and back sides of the barrier. Design details for the New Jersey Barrier Curb are shown in Figure K.1-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. However, New Jersey barriers have not been tested at heights below 32 in., and therefore, 32 in. is considered the minimum TL-3 height requirement. Thus, the 34-in. tall, New Jersey Barrier Curb has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

The New Jersey traffic face geometry has been successfully crash tested according to MASH test designation nos. 3-10 and 3-11 with the 1100C small car and the 2270P pickup truck, respectively [4–5]. Thus, the New Jersey traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [6], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table K.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table K.1-1. Effective Loads for Design of MASH Barriers [7]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis of the New Jersey Barrier Curb was conducted on the full barrier section as well as the upper section of the barrier. The full section had a strength of 228 kips for interior sections and 144 kips for end sections adjacent to discontinuities (expansion gaps and joints). The upper section of the barrier had a strength of 339 kips for interior sections and 246 kips for end sections. The punching shear capacity of the barrier was 224 kips at interior sections and 171 kips at end sections. All capacities were greater than the required 70 kips, and therefore, the New Jersey Barrier Curb satisfies the MASH TL-3 loading criteria for interior and end sections.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the New Jersey 34-in. Barrier Curb is believed to be crashworthy and in compliance with MASH TL-3. The evaluation is summarized in Table K.1-2.

Table K.1-2. New Jersey 34-in. Barrier Curb Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 34 in.		≥ 32 in. Pass	≥ 36 in. Inconclusive
Shape		New Jersey		Pass	Not Evaluated due to Inconclusive Stability Criterion
Strength	Yield Line	Interior	228 kips	≥ 70 kips Pass	
		End	144 kips		
	Punching Shear	Interior	224 kips		
		End	171 kips		
	Anchorage	Reinforcement		Pass	
Overall MASH Evaluation				Pass	Inconclusive

K.1.1 References

1. *Bridge Construction Details Pending 12/14/2018*, *BCD-507-3.1*, New Jersey Department of Transportation - Bureau of Structural Engineering, 2018.

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

3. Silvestri-Dobrovolny, C., Schulz, N., Moran, S., Skinner, T., Bligh, R.P., and Williams, W., *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, National Cooperative Highway Research Program (NCHRP) Report No. 20-07(395), Texas Transportation Institute, College Station, TX, November 2017.

4. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, B.W., Reid, J.D., Coon, B.A., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier-Update to NCHRP 350 Test No. 3-10 (2214NJ-1)*, Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 13, 2006

5. Bullard, D.L., Bligh, R.P., Menges, W.L., Haug, R.R., *Volume I: Evaluation of Existing Roadside Safety Hardware Using Updated Criteria*, National Cooperative Highway Research Program (NCHRP) Report 22-14(03), Texas Transportation Institute, College Station, TX, March 2010.

6. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

7. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

K.2. MASH Equivalency of the New Jersey DOT Concrete Median and Split Median Barriers

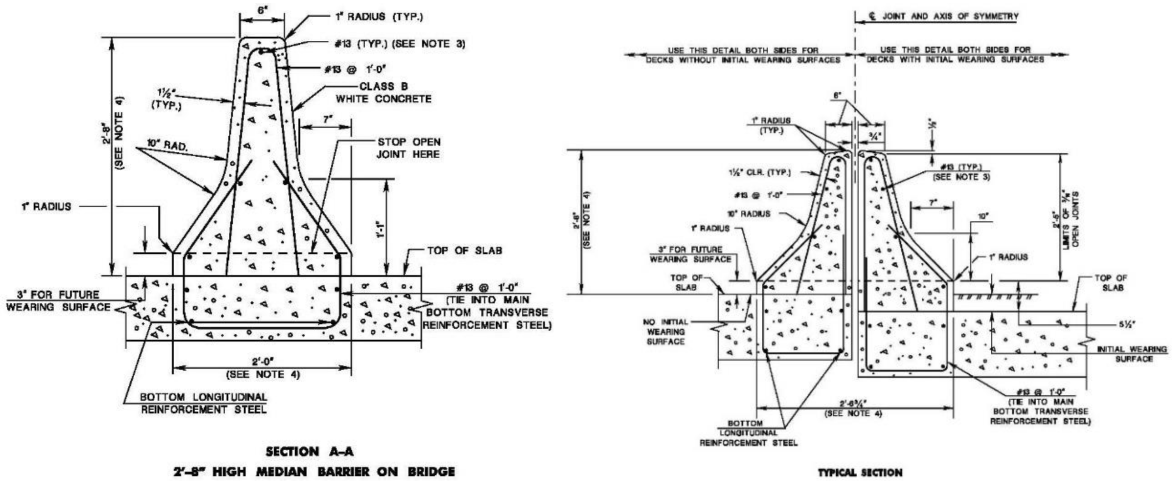


Figure K.2-1. New Jersey DOT 32-in. Median and Split Median Barrier Details []

<u>Overview and Stability Evaluation</u>

The New Jersey DOT Concrete Median and Split Median barriers are 32-in. tall, New Jersey shape reinforced concrete barriers with a 6-in. top width. The barrier is vertically reinforced with #4 bars spaced at 12 in. and is anchored to a concrete slab or bridge deck with #4 bent bars, also spaced at 12 in. Longitudinal reinforcement consists of five #4 bars in the Median Barrier and four #4 bars in the Split Median Barrier. Design details for the New Jersey Concrete Median and Split Median barriers are shown in Figure K.2-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. However, New Jersey barriers have not been tested at heights below 32 in., and therefore, 32 in. is considered the minimum TL-3 height requirement. Thus, the 32-in. tall, New Jersey Barrier Curb has the required height to contain the pickup truck under MASH TL-3 impact conditions.

<u>Shape Evaluation</u>

The New Jersey traffic face geometry has been successfully crash tested according to MASH test designation nos. 3-10 and 3-11 with the 1100C small car and the 2270P pickup truck, respectively [4–5]. Thus, the New Jersey traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [6], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table K.2-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Yield line analyses were conducted on the full barrier section and the upper section of the barrier. Additionally, the New Jersey Concrete Median and Split Median barriers were analyzed for punching shear strength in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. The results of the yield line and punching shear analyses are summarized in Table K.2-2.

Table K.2-1. Effective Loads for Design of MASH Barriers [7]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Table K.2-2. Computational Analysis Results for the Median and Split Median Barriers

Barrier Type	Yield Line Strength, kips		Punching Shear Strength, kips	
	Interior Sections, Full Barrier (Upper Portion)	End Sections, Full Barrier (Upper Portion)	Interior Sections	End Sections
Median	100 (98)	55 (65)	108	90
Split Median	70 (76)	41 (73)	91	75

Both the median and split median barriers had calculated punching shear and interior section yield line strengths sufficient to resist MASH TL-3 impacts. However, the end section yield line strengths were below the required 70 kips, and therefore, analytical methods could not justify barrier strength for MASH TL-3 loading.

Overall Evaluation

While the evaluation indicated that barrier height and geometry met MASH TL-3 criteria, the strength and anchorage of the New Jersey Concrete Median Barrier and the New Jersey Split Median Barrier could not be qualified by computation. Therefore, as summarized in Tables K.2-3 and K.2-4, the TL-3 evaluations of the barriers were inconclusive.

Table K.2-3. New Jersey 32-in Concrete Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 32 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">New Jersey</td><td>Pass</td><td rowspan="6">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>98 kips</td><td rowspan="4">≥ 70 kips
Inconclusive</td></tr>
<tr><td>End</td><td>55 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>108 kips</td></tr>
<tr><td>End</td><td>90 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Fail</td></tr>
</table>

Table K.2-4. New Jersey 32-in Split Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 32 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">New Jersey</td><td>Pass</td><td rowspan="6">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>70 kips</td><td rowspan="4">≥ 70 kips
Inconclusive</td></tr>
<tr><td>End</td><td>41 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>91 kips</td></tr>
<tr><td>End</td><td>75 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Fail</td></tr>
</table>

K.2.1 References

1. *Bridge Construction Details, Bridge Median Barrier, BCD-507-9*, New Jersey Department of Transportation - Bureau of Structural Engineering. Accessed 2019.

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

3. Silvestri-Dobrovolny, C., Schulz, N., Moran, S., Skinner, T., Bligh, R.P., and Williams, W., *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, National Cooperative Highway Research Program (NCHRP) Report No. 20-07(395), Texas Transportation Institute, College Station, TX, November 2017.

4. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, B.W., Reid, J.D., Coon, B.A., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier-Update to NCHRP 350 Test No. 3-10 (2214NJ-1)*, Report No. TRP-03-177-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 13, 2006

5. Bullard, D.L., Bligh, R.P., Menges, W.L., Haug, R.R., *Volume I: Evaluation of Existing Roadside Safety Hardware Using Updated Criteria*, National Cooperative Highway Research Program (NCHRP) Report 22-14(03), Texas Transportation Institute, College Station, TX, March 2010.

6. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

7. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

K.3. MASH Equivalency of New Jersey DOT 32-in. Barrier Curb

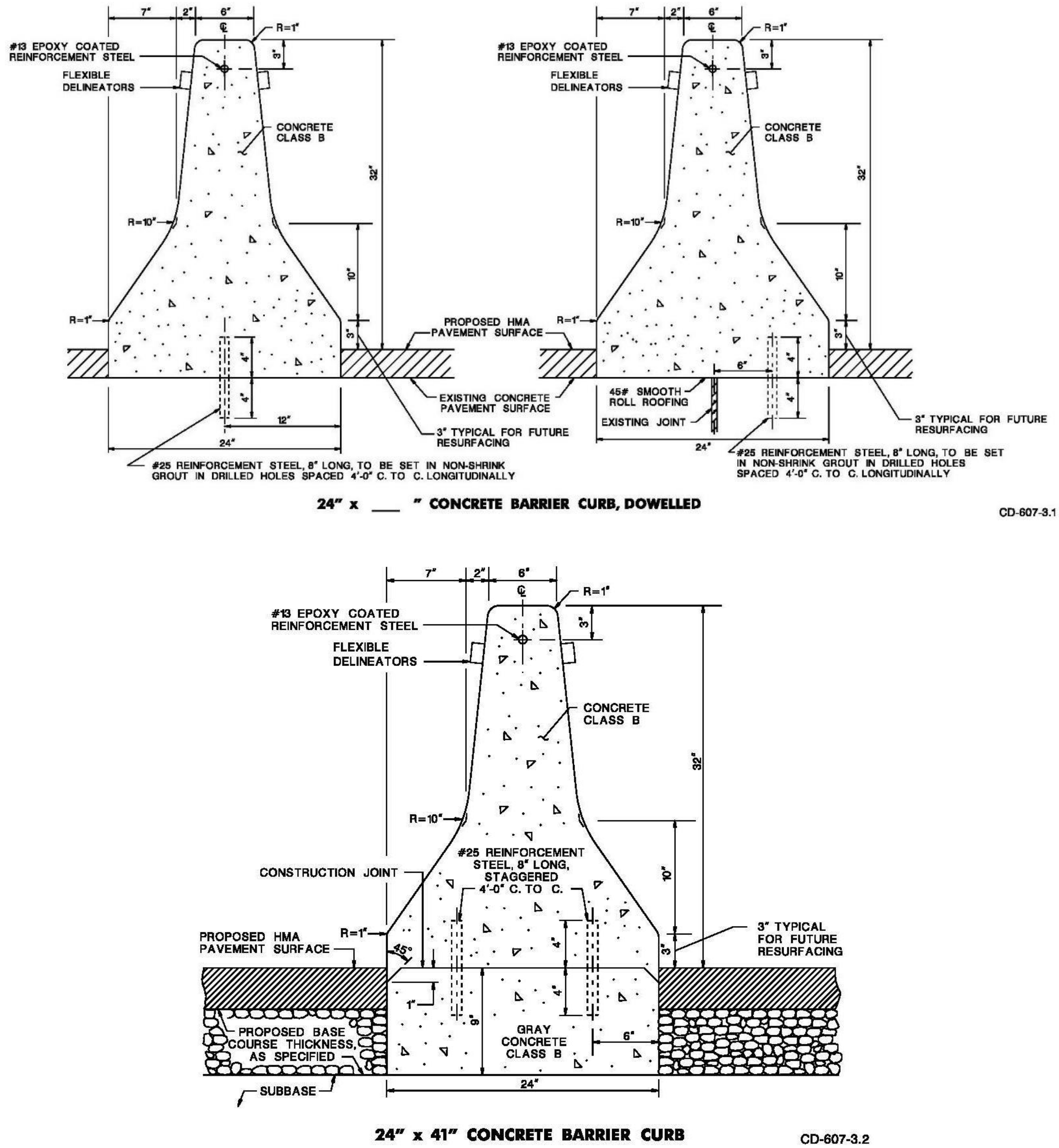


Figure K.3-1. New Jersey DOT 32-in. Concrete Barrier Curb Details [1]

Overview and Stability Evaluation

The New Jersey DOT Barrier Curb is a 32-in. tall, New Jersey Shape reinforced concrete median barrier with a 6-in. top width. The barrier is vertically unreinforced and is longitudinally reinforced by a single #4 reinforcing bar located 3 in. from the top of the barrier. Anchorage is provided by #8 bars drilled and grouted into existing concrete or staggered #8 bars cast into a 9-in. deep by 24-in. wide independent footing. In either case, the bars are spaced 4 ft on center. Design details for the New Jersey Barrier Curb are shown in Figure K.3-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. New Jersey barriers have been successfully tested at heights as low as 32 in. [3–4], and therefore, 32 in. is considered the minimum TL-3 height requirement. Thus, the 32-in. tall, New Jersey Barrier Curb has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

The New Jersey traffic face geometry has been successfully crash tested according to MASH test designation nos. 3-10 and 3-11 with the 1100C small car and the 2270P pickup truck, respectively [3–4]. Thus, the New Jersey traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

As a minimally reinforced barrier, the Barrier Curb is outside the scope of the conventional yield line analysis presented in the AASHTO LRFD Bridge Design Specifications [5]. A punching shear analysis of both interior and end sections could still be conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design specifications, with load requirements updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table K.3-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length.

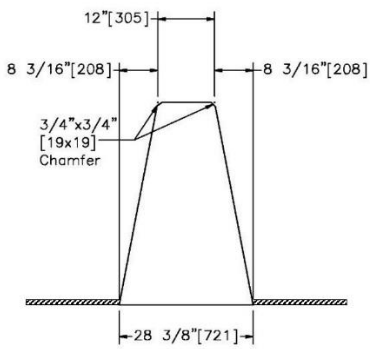
Table K.3-1. Effective Loads for the Design of MASH

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

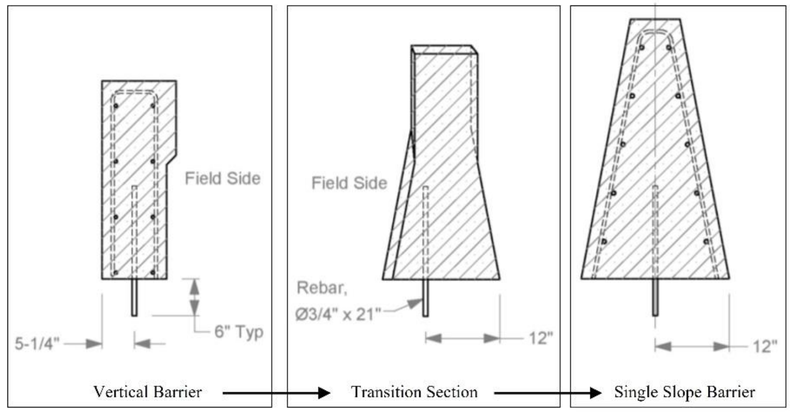
The punching shear capacity of the median barrier at the interior and end sections was 100 kips and 83 kips, respectively. These calculated capacities were greater than the required 70 kips, but because the yield line strength could not be calculated for the minimally reinforced barrier, analytical methods could not conclusively evaluate the barrier strength.

Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Barrier Curb. Currently, no crash tests have been performed on barriers with only longitudinal reinforcement. However, an unreinforced single-slope barrier with asphalt keyway anchorage [7] and a concrete barrier with dowel anchorage [8] have been crash tested to MASH TL-3. The profiles of the crash tested barriers are shown in Figure K.3-2.



Test No. OSSB-1



TxDOT T221 Transition

Figure K.3-2. Test No. OSSB-1 Barrier [7] and TxDOT T221 Transition Barrier [8] Profiles

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [7]. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier is a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [8]. A comparison of the two crash tested systems with the Type C Median Barrier is provided in Table K.3-2.

Table K.3-2. Anchorage Comparison for New Jersey 32-in. Barrier Curb

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT T221[(a)] 469689-2-2 (TL-3)	New Jersey 32-in. Barrier Curb	
Barrier Shape		Single-Slope	Transition: Single-Slope and Vertical	New Jersey	
Anchorage	Type	Asphalt Keyway	1 x #6 Dowels	1 x #8 Dowels with Asphalt Keyway	Staggered #8 Dowels with Footing
	Depth	1 in.	21-in. bar (Embed 6 in.)	8-in. bar (Embed 4 in.) 3-in. Keyway [(b)]	8-in. bar (Embed 4 in.) 9-in. Footing
	Spacing	Continuous	8 ft	4 ft	
Geometry	Base Width	28⅜ in.	18 in.	24 in.	
	Top Width	12 in.	10 in.	6 in.	
	Height	43 in.	37 in.	32 in.	
Reinf.	Longitudinal	--	10 x #5	4 x #5	
	Vertical	--	2 x #5 @ 12 in.	--	
Stability	Section Weight	904 plf	540 plf	410 plf	
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	410 ft-lb	
	Overturning Demand	140 kip-ft	200 kip-ft	140 kip-ft	

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.
(b) Keyway depth is estimated. Exact depth is not dimensioned on New Jersey standard plans.

The New Jersey Barrier Curb was 11-in. shorter and 4-in. narrower than the unreinforced barrier evaluated in test no. OSSB-1. While the #4 longitudinal reinforcement in the Barrier Curb would provide increased strength compared to the unreinforced barrier, the differences in size and traffic face geometry were significant enough that test no. OSSB-1 could not reasonably justify a MASH evaluation of the Barrier Curb strength.

The TxDOT T221 transition was anchored by #6 bars spaced at 8-ft intervals, and each 21-in. long dowel had a 6-in. embedment depth. Both anchorage configurations of the Barrier Curb use #8 bars spaced at 4-ft intervals and embedded 4 in. While the bar length and embedment are reduced compared to the TxDOT T221 transition, the larger bar size and tighter spacing mean that per unit length, the Barrier Curb provides over three times the bar area of the TxDOT T221 transition, which suggests the anchorage strength may be equal to or greater than the MASH TL-3 TxDOT T221 transition barrier. However, the combined differences in barrier geometry and reinforcing are significant enough that the TxDOT T221 transition barrier system performance cannot adequately justify the 32-in. Barrier Curb strength.

While the test no. OSSB-1 and TxDOT T221 transition barrier systems provided valuable information on the crashworthiness of unreinforced barriers and dowel-bar anchorages, the geometric differences were such that the 32-in. Barrier Curb strength evaluation remained inconclusive.

Overall Evaluation

Although the 32-in. tall Barrier Curb has similar characteristics to some crash tested systems, no crash testing has been performed on a minimally reinforced New Jersey barrier that could be used to qualify barrier strength and anchorage. Therefore, the TL-3 evaluation of the New Jersey 32-in. Barrier Curb is inconclusive.

Table K.3-3. New Jersey 32-in. Barrier Curb Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 32 in.</td><td>≥ 32 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">New Jersey</td><td>Pass</td><td></td></tr>
<tr><td rowspan="6">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>--</td><td rowspan="4">≥ 70 kips
Inconclusive</td><td rowspan="6">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td>End</td><td>--</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>100 kips</td></tr>
<tr><td>End</td><td>83 kips</td></tr>
<tr><td rowspan="2">Anchorage</td><td colspan="2">#8 Dowel with Existing Pavement</td><td>Inconclusive</td></tr>
<tr><td colspan="2">#8 Dowel with Footing</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Fail</td></tr>
</table>

K.3.1 References

1. *Construction Details*, *CD-607-3*, New Jersey Department of Transportation - Bureau of Structural Engineering. Accessed 2019.

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

3. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, B.W., Reid, J.D., Coon, B.A., *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier-Update to NCHRP 350 Test No. 3-10 (2214NJ-1)*, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 13, 2006

4. Bullard, D.L., Bligh, R.P., Menges, W.L., Haug, R.R., *Volume I: Evaluation of Existing Roadside Safety Hardware Using Updated Criteria*, National Cooperative Highway Research Program (NCHRP) Report 22-14(03), Texas Transportation Institute, College Station, TX, March 2010.

5. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

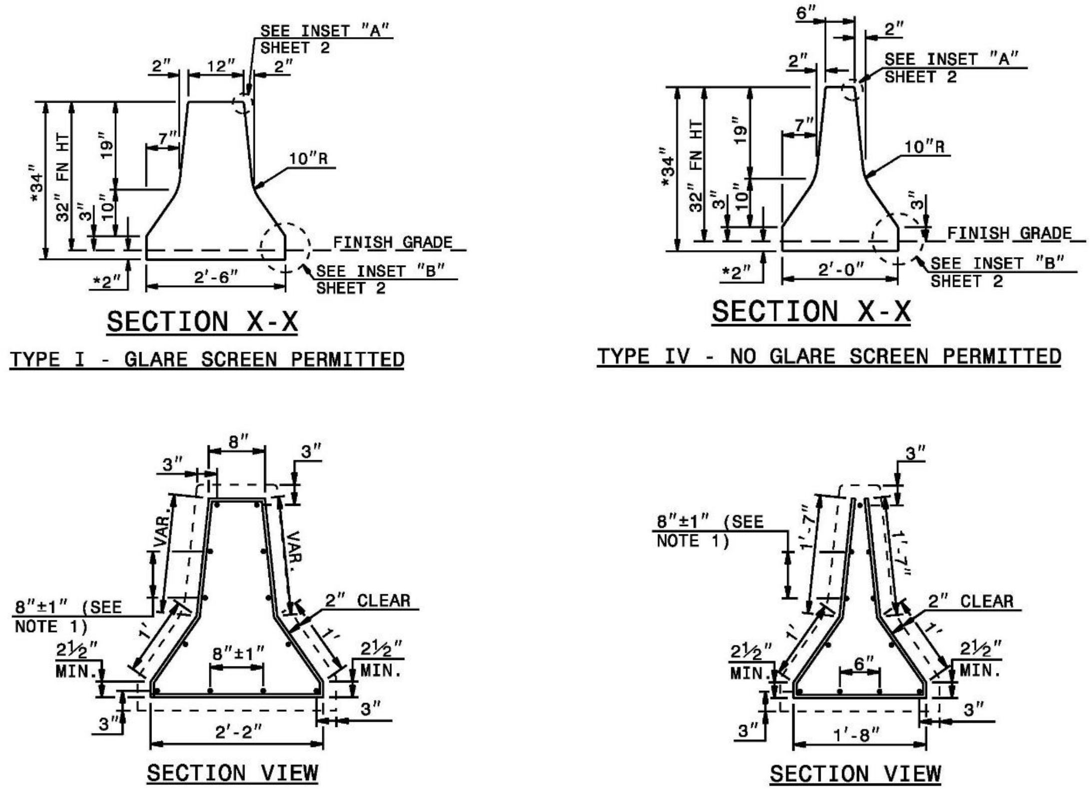
6. Bligh, R.P., Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

7. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced*, *Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.

8. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

Appendix L. North Carolina Permanent Concrete Barrier MASH Evaluations

L.1. MASH Equivalency of the North Carolina DOT Type I and IV Barriers



Type I Barrier *Type IV Barrier*

Figure L.1-1. North Carolina DOT Type I and IV Barrier Details [1]

Overview and Stability Evaluation

The North Carolina DOT Type I and IV concrete barriers are a 32-in. tall, New Jersey Shape reinforced concrete median barriers. The Type I barrier features top and bottom widths of 12-in. and 30-in., respectively, while the Type IV barrier is 6 in. narrower. Vertical reinforcement details for both barriers give options for #4 bars spaced at 12 in. or #5 bars spaced at 18 in. Longitudinal reinforcement is provided by #4 bars distributed around the barrier perimeter at 8-in. nominal spacing. In total, 12 longitudinal bars are used for the Type I and 11 bars are used for the Type IV. Anchorage is provided by a 2 in. asphalt keyway. Design details for the North Carolina Type I and IV Barriers are shown in Figure L.1-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. New Jersey barriers have previously passed MASH TL-3 criteria at heights as low as 32 in. [3–4], and therefore, 32 in. is considered the minimum MASH TL-3 height requirement for New Jersey shaped barriers. Thus, the 32-in. Type I and IV barriers have the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

The New Jersey traffic face geometry has been successfully crash tested according to MASH test designation nos. 3-10 and 3-11 with the 1100C small car and the 2270P pickup truck, respectively [3–4]. Thus, the New Jersey traffic face geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [5], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table L.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. Yield line analyses were conducted for both the full barrier section and the upper section of each barrier, and the lower capacity was used for MASH evaluation. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. The results of the yield line and punching shear analyses are summarized in Table L.1-2.

Table L.1-1. Effective Loads for Design of MASH Barriers [6]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

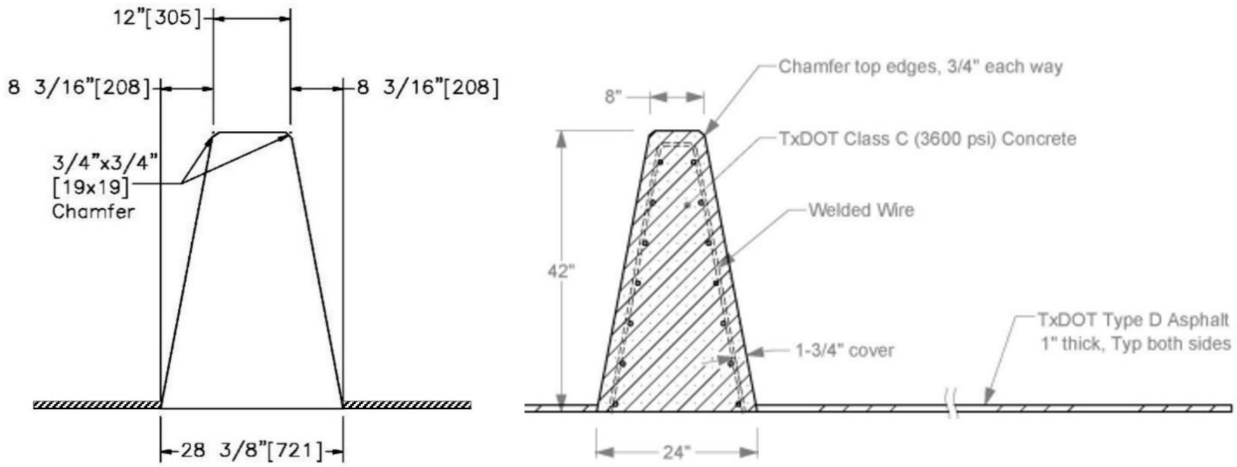
Table L.1-2. Computational Analysis Results for the Type I and Type IV Barriers

Barrier Type	Yield Line Strength, kips		Punching Shear Strength, kips	
	Interior Sections, Full Barrier (Upper Portion)	End Sections, Full Barrier (Upper Portion)	Interior Sections	End Sections
Type I	214 (220)	85 (130)	250	207
Type IV	121 (115)	56 (70)	110	92

For the Type I barrier, all calculated strengths were greater than the required 70 kips, and therefore, the Type I barrier meets the MASH TL-3 loading criteria. For the Type IV barrier, the calculated strength at end sections was below the required 70 kips, and therefore, analytical methods could not conclusively justify Type IV barrier strength for MASH TL-3 loading. In addition, the adequacy of the asphalt keyway anchorage details must be evaluated for both barriers. As discussed below, existing crash test data was reviewed to evaluate the MASH TL-3 performance of the keyway anchorage

Direct Comparison of Strength and Anchorage

Currently, no crash tests have been performed on New Jersey shaped barriers with asphalt keyway anchorages. However, two crash tests have been conducted on 42-in. tall single-slope concrete barriers with asphalt keyway anchorages. The barrier profiles for the two crash tested systems are shown in Figure L.1-2.



Test No. OSSB-1 TxDOT 42-in. SSCB

Figure L.1-2. Barrier Profiles for Test Nos. OSSB-1 [7] and 469467-3-1 (TxDOT 42-in. SSCB) [8]

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [7]. In a TL-4 evaluation, a TxDOT 42-in. SSCB anchored by a 1-in. asphalt keyway was crash tested in accordance with MASH test designation no. 4-12 [8]. A comparison of the two crash tested systems with the North Carolina Type I and Type IV barriers is provided in Table L.1-3.

Table L.1-3. North Carolina Type I and IV Asphalt Keyway Comparison

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT SSCB 469467-3-1 (TL-4)	NC Type I	NC Type IV
Asphalt Keyway Depth		1 in.	1 in.	2 in.	2 in.
Barrier Shape		Single-Slope	Single-Slope	New Jersey	New Jersey
Geometry	Base Width	28⅜ in.	24 in.	30 in.	24 in.
	Top Width	12 in.	8 in.	12 in.	6 in.
	Height	43 in.	42 in.	32 in.	32 in.
Reinforcement	Longitudinal	--	14 x D18WWR	12 x #4	11 x #4
	Vertical	--	D9 WWR @ 8 in.	#4 @ 12 in. or #5 @ 18 in.	#4 @ 12 in. or #5 @ 18 in.
Stability	Section Weight	904 plf	700 plf	654 plf	454 plf
	Overturning Stability per ft	1068 ft-lb	700 ft-lb	817 ft-lb	454 ft-lb

The Type I barrier was shorter and wider at the base than the two crash tested barriers, and the estimated inertial overturning resistance was intermediate between the TL-3 and TL-4 tested barriers. In addition, as part of the research associated with test no. OSSB-1, the 1-in. asphalt keyway was assessed as a critical anchorage configuration. Therefore, the 2-in. asphalt keyway used with the Type I barrier is expected to provide increased anchorage resistance compared to the crash tested barrier configurations and is assessed as having sufficient strength to resist MASH TL-3 impacts.

In contrast, the Type IV barrier section is significantly smaller than both the TxDOT SSCB system and the test no. OSSB-1 barrier. While the Type IV may be crashworthy to MASH TL-3, the posited benefits of the 2-in. keyway are insufficient to justify a crashworthy evaluation.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the North Carolina Type I barrier is believed to be crashworthy and in compliance with MASH TL-3. The strength and anchorage of the Type IV barrier could not be qualified by computation or direct comparison, and therefore, the TL-3 crashworthiness of the North Carolina Type IV barrier is inconclusive. The barrier evaluations are summarized in Tables L.1-4 L.1-5.

Table L.1-4. North Carolina Type I Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation TL-3	MASH Evaluation TL-4
Stability		Height = 32 in.		≥ 32 in. Pass	≥ 36 in. Fail
Shape		New Jersey		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	214 kips	≥ 70 kips Pass	
		End	85 kips		
	Punching Shear	Interior	250 kips		
		End	207 kips		
	Anchorage	2-in. Asphalt Keyway		Pass*	
Overall MASH Evaluation				Pass	Fail

* Justified based on available crash tests or finite element simulations.

Table L.1-5. North Carolina Type IV Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation TL-3	MASH Evaluation TL-4
Stability		Height = 32 in.		≥ 32 in. Pass	≥ 36 in. Fail
Shape		New Jersey		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	115 kips	≥ 70 kips Inconclusive	
		End	56 kips		
	Punching Shear	Interior	110 kips		
		End	92 kips		
	Anchorage	2-in. Asphalt Keyway		Inconclusive	
Overall MASH Evaluation				Inconclusive	Fail

L.1.1 References

1. Roadway Standard Drawing for Double Faced Concrete Barrier Types I, II, III & IV, 854.01, Sheet 1 of 4, State of North Carolina Dept. of Transportation, Division of Highways, Raleigh, NC, 2018.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
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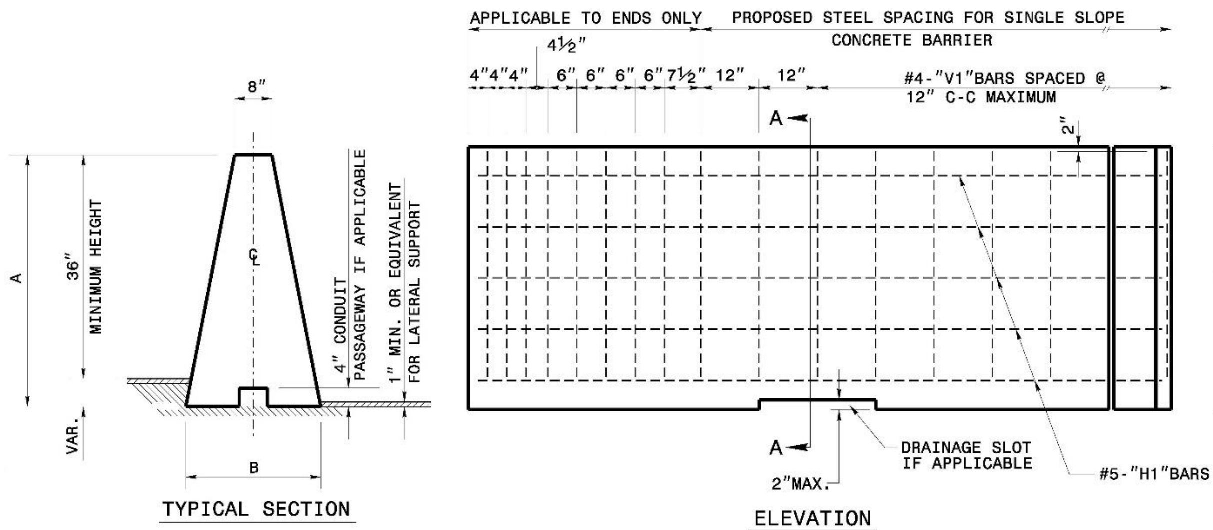
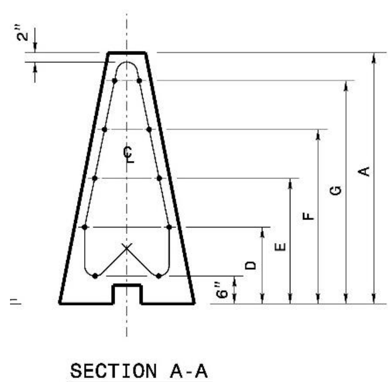
L.2. MASH Equivalency of the North Carolina 42-in., 48-in., and 52-in. Single-Slope Barriers





BARRIER HEIGHT (IN.)	A	B	D	E	F	G	K	L	M	N	O	P
42"	42	24	13½	21	28½	36	15	9¼	36	72	28	4
48"	48	26 9/32	15	24	33	42	17½	10¾	42	84	31½	5
52"	54	28 9/16	16½	27	37½	48	19½	12¼	48	96	34¾	6

Figure L.2-1. North Carolina DOT Single-Slope Concrete Barriers [1]

Overview and Stability Evaluation

The North Carolina DOT 42SS, 48SS, and 52SS are reinforced concrete barriers with a 10.8-degree single-slope traffic face and heights of 42, 48, and 52 in. The barriers are vertically reinforced with #4 stirrups spaced at 12-in. and longitudinally reinforced with five #5 bars on both the front and back sides of the barrier. Anchorage is provided by an asphalt keyway with a minimum thickness of 1 in. Design details for the North Carolina Single-Slope Barrier series are shown in Figure L.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no.

4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in., 48-in., and 52-in. tall North Carolina Single-Slope Barriers have the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

The single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table L.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Additionally, a punching shear analysis was conducted in accordance with Section 5 of AASHTO LRFD Bridge Design Specifications. The results of the computational analysis are summarized in Table L.2-2.

Table L.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

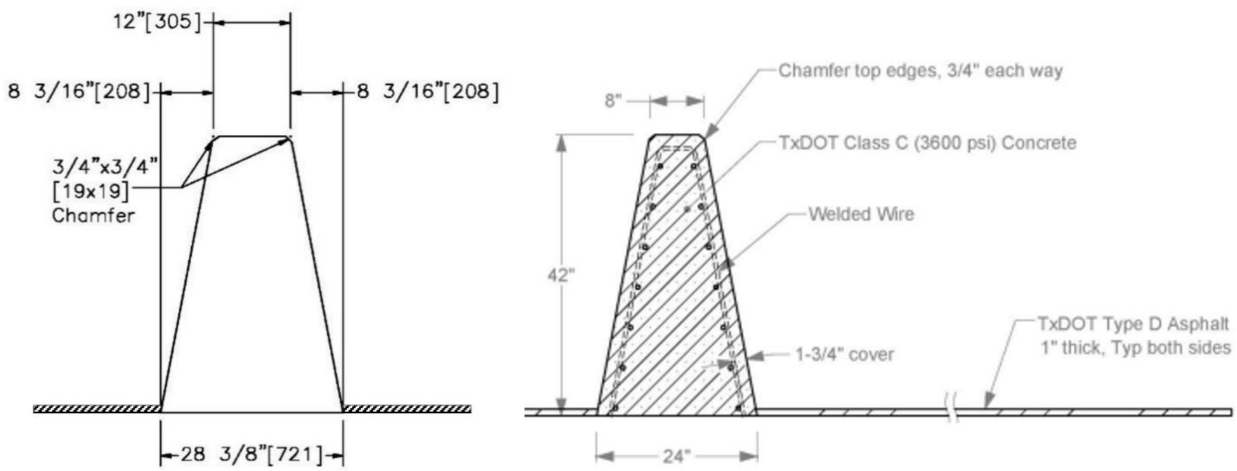
Table L.2-2. Computational Analysis Results for North Carolina 42SS, 48SS, and 52SS Barriers

Barrier Configuration	Yield Line Strength		Punching Shear Strength	
	Interior Section	End Section	Interior Section	End Section
42SS	190 kips	121 kips	269 kips	219 kips
48SS	217 kips	135 kips	362 kips	289 kips
52SS	267 kips	148 kips	434 kips	320 kips

All calculated capacities were greater than the required 80 kips, and therefore, the 42-in., 48-in., and 52-in. North Carolina Single-Slope Barriers satisfy MASH TL-4 loading criteria for interior and end sections. While the yield line and punching shear analyses are favorable, the adequacy of the asphalt keyway anchorage must also be evaluated.

Direct Comparison of Strength and Anchorage

Existing research on keyway-anchored permanent concrete barriers is limited, but two crash tests have been conducted on 42-in. tall single-slope concrete barriers with asphalt keyway anchorages. The barrier profiles for the two crash tested systems are shown in Figure L.2-2.



Test No. OSSB-1 TxDOT 42-in. SSCB

Figure L.2-2. Barrier Profiles for Test Nos. OSSB-1 [6] and 469467-3-1 (TxDOT 42-in. SSCB) [10]

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. In a TL-4 evaluation, a TxDOT 42-in. SSCB anchored by a 1-in. asphalt keyway was crash tested in accordance with MASH test designation no. 4-12 [10]. The reinforced, single-slope concrete barrier contained and redirected the 10000S vehicle with minimal system deflections and barrier damage. A comparison of the two crash tested systems with the North Carolina Single-Slope Barriers is provided in Table L.2-3.

Table L.2-3. North Carolina Single-Slope Barrier Anchorage Comparison

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT SSCB 469467-3-1 (TL-4)	North Carolina Single-Slope		
				42SS	48SS	52SS
Asphalt Keyway Depth		1 in.	1 in.	1 in.		
Geometry	Base Width	$28\frac{3}{8}$ in.	24 in.	24 in.	$26\frac{9}{32}$ in.	$28\frac{9}{16}$ in.
	Top Width	12 in.	8 in.	8 in.		
	Height	43 in.	42 in.	42 in.	48 in.	52 in.
Reinf.	Longitudinal	--	14 x D18 WWR	10 x #5		
	Vertical	--	D9 WWR @ 8 in.	#4 @ 12 in.		
Stability	Section Weight	904 plf	700 plf	700 plf	857 plf	990 plf
	Overturning Stability per ft	1068 ft-lb	700 ft-lb	700 ft-lb	938 ft-lb	1178 ft-lb

The 42SS barrier has very similar parameters to the TxDOT SSCB. The barrier reinforcing patterns differ but the yield line and punching shear analyses demonstrated that the North Carolina Single-Slope Barriers have adequate strength for TL-4 impacts. The 48SS and 52SS configurations have larger base widths and section weights than the 42SS configuration and are expected to equal or exceed the resistance of the 42SS barrier. Therefore, the 42SS, 48SS, and 52SS barriers configured with a 1-in. asphalt keyway possesses the required anchorage to withstand a TL-4 impact.

<u>Overall Evaluation</u>

Based on this evaluation of height, geometry, strength, and anchorage, the North Carolina 42-in., 48-in., and 52-in. Single-Slope Barriers are believed to be crashworthy and in compliance with MASH TL-4. The barrier evaluations are summarized in Tables L.2-4 through L.2-6.

Table L.2-4. North Carolina 42-in. Single-Slope Concrete Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	TL-4
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	190 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	121 kips		
	Punching Shear	Interior	269 kips		
		End	219 kips		
	Anchorage	1-in. Asphalt Keyway		Pass*	Pass*
Overall MASH Evaluation				Pass	Pass

* Justified based on available crash tests or finite element simulations.

Table L.2-5. North Carolina 48-in. Single-Slope Concrete Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	TL-4
Stability		Height = 48 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	217 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	135 kips		
	Punching Shear	Interior	362 kips		
		End	289 kips		
	Anchorage	1-in. Asphalt Keyway		Pass*	Pass*
Overall MASH Evaluation				Pass	Pass

* Justified based on available crash tests or finite element simulations.

Table L.2-6. North Carolina 52-in. Single-Slope Concrete Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	TL-4
Stability		Height = 52 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	267 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	148 kips		
	Punching Shear	Interior	434 kips		
		End	320 kips		
	Anchorage	1-in. Asphalt Keyway		Pass*	Pass*
Overall MASH Evaluation				Pass	Pass

* Justified based on available crash tests or finite element simulations.

L.2.1 References

1. *Single Slope Concrete Barrier*, Contract Services & Development Unit, Standards and Special Design, North Carolina Department of Transportation, August 18, 2006.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.

7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.

9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

10. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase I*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.

Appendix M. Ohio Permanent Concrete Barrier MASH Evaluations

M.1. MASH Equivalency of the Ohio Type B and B1 Single-Slope Barriers

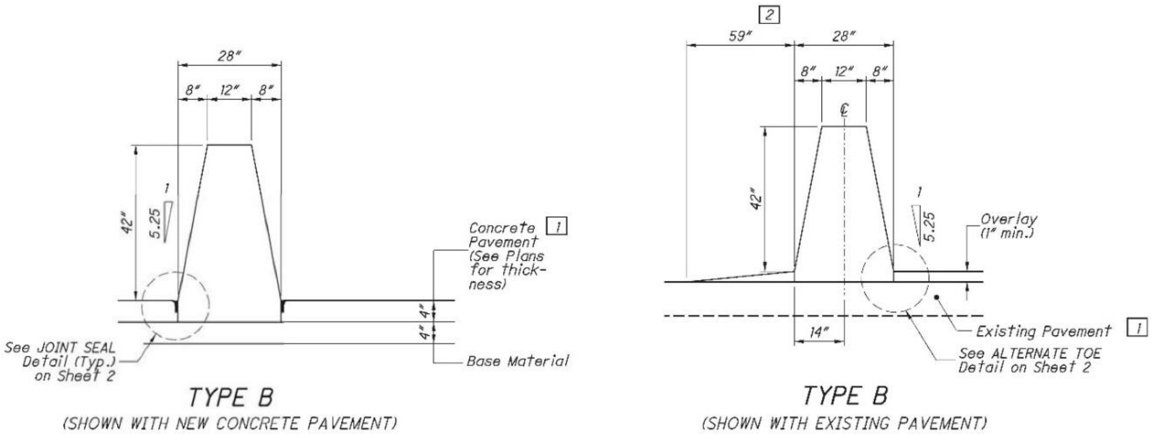


Figure M.1-1. Ohio DOT Type B Single-Slope Barrier [1]

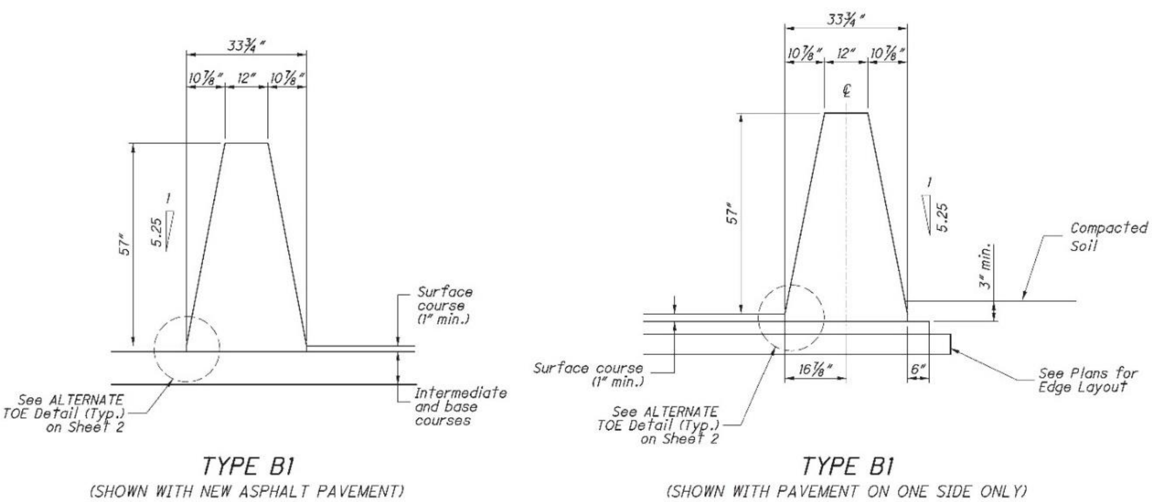


Figure M.1-2. Ohio DOT Type B1 Single-Slope Barrier [1]

<u>Overview and Stability Evaluation</u>

The Ohio DOT Type B and B1 barriers are 42-in. and 57-in. tall concrete barriers with a 10.8-degree single-slope traffic face. The barriers are only reinforced at end sections. Vertical reinforcement at end sections consists of six #4 stirrups spaced at 6 in. and an additional six #4 stirrups spaced at 24 in. End sections are longitudinally reinforced with #5 bars: four bars on both the front and back sides of the barrier, and one additional #5 bar placed near the top of the barrier. Barrier ends and expansion joints are detailed with a 9-in. deep by 15-ft long concrete end anchorage that is reinforced by four longitudinal #5 bars. Three anchorage alternatives are provided: a 1-in. asphalt keyway, a 4-in. pavement keyway, and #8 dowels embedded into existing concrete pavement and staggered at a maximum of 4 ft on center. Additional anchorages were noted in the Ohio details. However, a previous research effort involving MASH TL-3 full-scale crash testing of the 42-in. tall version of this barrier identified these three anchorages as the primary anchorage designs used by Ohio and identified the 1-in. asphalt keyway as the critical anchorage configuration [6]. Design details for configurations of the barriers are shown in Figures M.1-1 and

M.1-2. The Type B barrier with a 1-in. asphalt keyway was crash tested in test no. OSSB-1 and met the criteria of MASH test designation no. 3-11 [6]. Additionally, as part of that research effort, the 4-in. concrete keyway and staggered #8 dowel bar anchorages were assessed as less critical than the 1-in. asphalt keyway anchorage system. Therefore, the Type B barrier is believed to be crashworthy to MASH TL-3.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. and 57-in. Type B and Type B1 barriers have the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table M.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Because interior sections of both the Type B and Type B1 barriers were unreinforced, only the end sections could be evaluated by yield line analysis. A punching shear analysis was conducted for interior and end sections of both barriers in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. At end sections, the punching shear analysis included the resistance of both concrete and vertical reinforcement.

Table M.1-1. Effective Loads for Design of MASH Barriers [3]

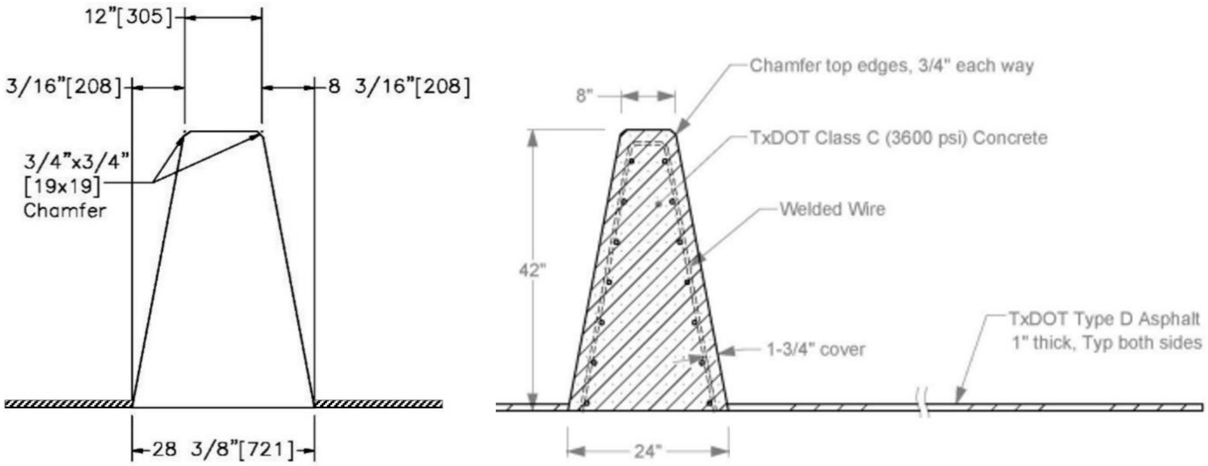
Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis of the end sections determined strength to be 76 kips for the Type B and 97 kips for the Type B1. The calculated capacity for The Type B barrier is below the 80 kips required for TL-4 impacts. The barrier has demonstrated the capacity for MASH TL-3 impacts based on the full-scale crash testing denoted previously. The punching shear capacity of the Type B barriers at interior and end sections was 397 kips and 315 kips, respectively. The punching shear capacity of the Type B1 barriers at interior and end sections was 650 kips and 484 kips, respectively. Therefore, the Type B1 barrier satisfies MASH TL-4 loading criteria for end sections, but without a yield line analysis or structural capacity analysis of the interior section, the strength of both barriers remains inclusive.

Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Type B and Type B1 barriers. Previous research and crash testing demonstrated that all three anchorage configurations of the Type B barrier were crashworthy to MASH TL-3 [6]. The test article in test no. OSSB-1 did not include the Ohio DOT end section details, and therefore, represented a more critical system configuration than the standard Type B barrier. The Type B1 is 15 in. taller and 5 in. wider at the base than the Type B. As a result, the section weight and static overturning resistance of the Type B1 are significantly higher than the Type B. Accordingly, the Type B1 is also considered crashworthy to TL-3.

There is a known TL-4 crash test of a concrete barrier with a keyway anchorage. A TxDOT 42-in. SSCB anchored by a 1-in. asphalt keyway was crash tested in accordance with MASH test designation no. 4-12 [10]. The reinforced, single-slope concrete barrier contained and redirected the 10000S vehicle with minimal system deflections and barrier damage. The barrier profiles for the Type B barrier evaluated in test no. OSSB-1 and the TL-4 crash tested TxDOT 42-in. SSCB system are shown in Figure M.1-3. A comparison with the Type B and Type B1 barriers is provided in Table M.1-2.



Test No. OSSB-1 TxDOT 42-in. SSCB

Figure M.1-3. Barrier Profiles for Test Nos. OSSB-1 [6] and 469467-3-1 (TxDOT 42-in. SSCB) [10]

Table M.1-2. Ohio Type B Anchorage Comparison

Evaluation Parameter		**Type B OSSB-1 (TL-3)**	**TxDOT SSCB 469467-3-1 (TL-4)**	**Ohio Type B**	**Ohio Type B1**
Barrier Shape		Single-Slope	Single-Slope	Single-Slope	
Anchorage		1-in. Asphalt Keyway	1-in. Asphalt Keyway	1-in. Asphalt Keyway 4-in. Concrete Keyway #8 Dowels @ 4 ft	
Geometry	Base Width	28⅜ in.	24 in.	28 in.	33¾ in.
	Top Width	12 in.	8 in.	12 in.	12 in.
	Height	43 in.	42 in.	42 in.	57 in.
Reinf.	Longitudinal	--	14 x D18 WWR	--	--
	Vertical	--	D9 WWR @ 8 in.	--	--
Stability	Section Weight	904 plf	700 plf	904 plf	1358 plf
	Overturning Stability per ft	1068 ft-lb	700 ft-lb	1068 ft-lb	1910 ft-lb

While the Type B and Type B1 provide equivalent anchorage to the TL-4 crashworthy TxDOT SSCB system, the unreinforced interior sections are not comparable to the crash tested system. This difference is significant, and therefore, the Type B and Type B1 barrier strengths remain inconclusive for MASH TL-4.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Ohio Type B and B1 barriers are believed to be crashworthy and in compliance with MASH TL-3 when configured with a 1 in. asphalt keyway, 4-in. concrete keyway, or staggered #8 dowel bars. The barriers may also be crashworthy and in compliance with MASH TL-4, but the absence of interior reinforcement makes it difficult to qualify barrier strength and anchorage. The evaluation of the barriers at MASH TL-4 was, therefore, inconclusive. The evaluations are summarized in Tables M.1-3 and M.1-4

Table M.1-3. Ohio Type B Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	76 kips		
	Punching Shear	Interior	397 kips		
		End	315 kips		
	Anchorage	1-in. Asphalt Keyway		Pass*	Inconclusive
		4-in. Concrete Keyway		Pass*	Inconclusive
		Staggered #8 Dowel Bars		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

Table M.1-4. Ohio Type B1 Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 57 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	97 kips		
	Punching Shear	Interior	650 kips		
		End	484 kips		
	Anchorage	1-in. Asphalt Keyway		Pass*	Inconclusive
		4-in. Concrete Keyway		Pass*	Inconclusive
		Staggered #8 Dowel Bars		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

M.1.1 References

1. *Single Slope Barrier, Types B, C, B1 & C1, RM-4.3, Page 1 of 2*, Office of Roadway Engineering, State of Ohio Department of Transportation, July 18, 2014.
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4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.
6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.
7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
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M.2. MASH Equivalency of Ohio DOT Type D Roadside Barrier

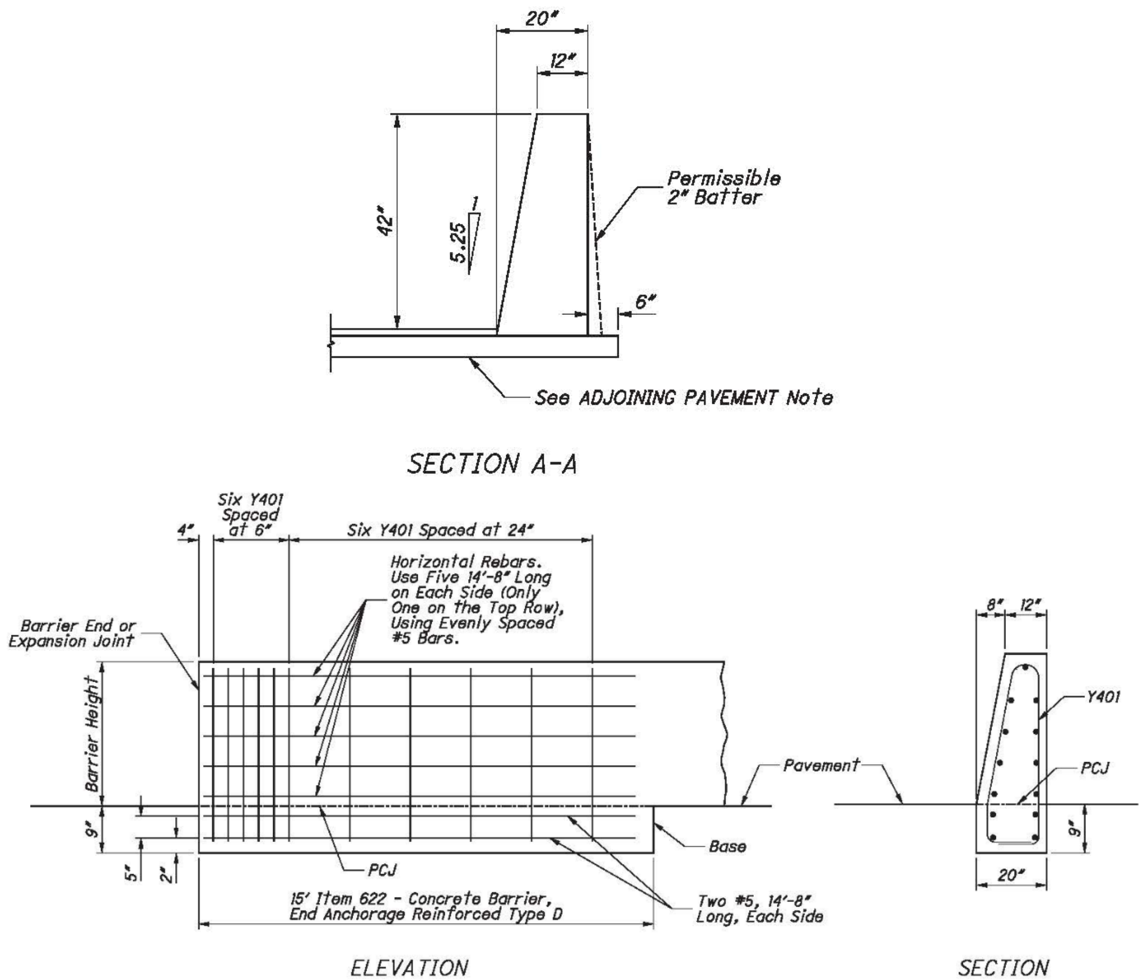


Figure M.2-1. Ohio Type D Roadside Barrier Details [1]

<u>Overview and Stability Evaluation</u>

The Ohio DOT Type D Roadside Barrier is a 42-in. tall concrete barrier with a 10.8-degree single-slope traffic face. The barrier is only reinforced at end sections. Vertical reinforcement at end sections consists of six #4 stirrups spaced at 6 in. and an additional six #4 stirrups spaced at 24 in. End sections are longitudinally reinforced with #5 bars: four bars on both the front and back sides of the barrier, and one additional #5 bar placed near the top of the barrier. Barrier ends and expansion joints are detailed with a 9-in. deep by 15-ft long concrete end anchorage that is reinforced by four longitudinal #5 bars. Anchorage is provided by either a 1-in. asphalt keyway or #8 dowels embedded into existing concrete pavement and staggered at a maximum of 4 ft on center. Design details for configurations of the barriers are shown in Figure M.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall Type D Roadside Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table M.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Because interior barrier sections were unreinforced, only the end section could be evaluated by yield line analysis. A punching shear analysis was conducted for interior and end sections in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. At end sections, the punching shear analysis included the resistance of both concrete and vertical reinforcement

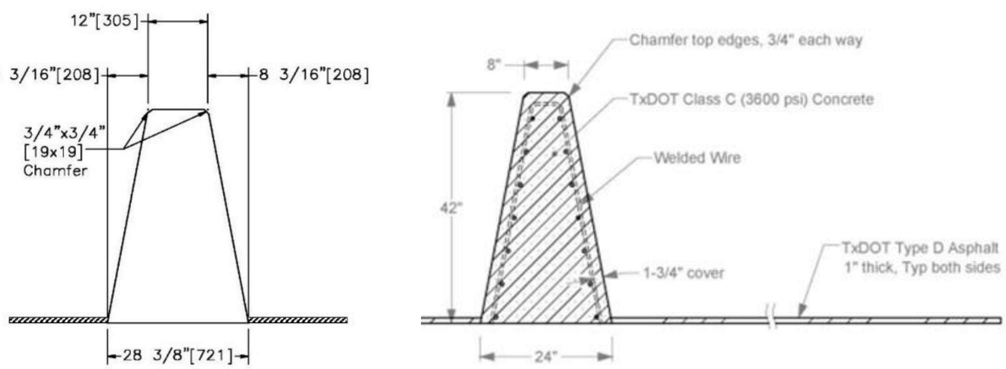
Table M.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis of the Type D Roadside barrier determined an end section strength of 51 kips. This is below the 70 kips required for MASH TL-3. Therefore, the barrier strength at the end sections does not meet the loading criteria for MASH TL-3 or TL-4. The punching shear capacity of the barrier at interior and end sections was 253 kips and 323 kips, respectively, which exceeds the MASH TL-4 design load. However, with an unsatisfactory calculation for end section yield line strength and no yield line analysis for the unreinforced interior sections, the strength of the barrier remains inconclusive.

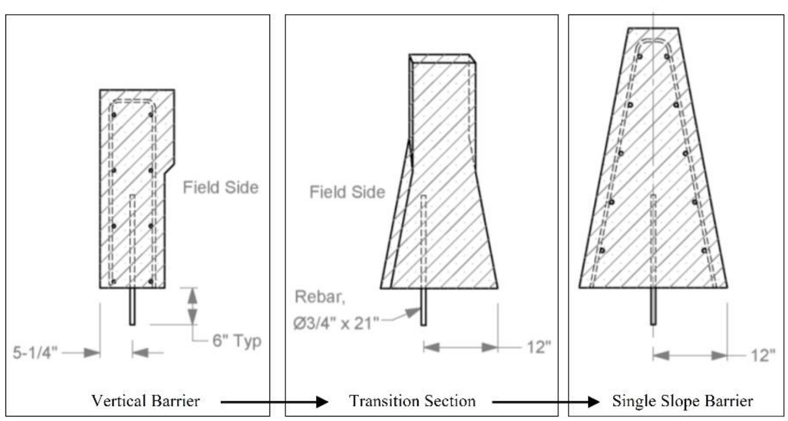
Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Type D barrier. No crash tests have been conducted on barriers with both unreinforced interior sections and dowel bar anchorages, but an unreinforced single-slope barrier with asphalt keyway anchorage and a reinforced barrier with dowel bar anchorage have been crash tested to MASH TL-3. A reinforced barrier with asphalt keyway anchorage has also been crash tested to TL-4 [10], but the difference in barrier reinforcement was considered significant, and therefore, this test could not be used to justify the MASH TL-4 crashworthiness of the Type D barrier. It nonetheless provided information on the performance of asphalt keyway anchorages. The profiles of the crash tested systems are shown in Figures M.2-2 M.2-3.



Test No. OSSB-1 [6]　　TxDOT 42-in. SSCB [10]

Figure M.2-2. Barrier Profiles for Crash Tested Asphalt Keyway Systems



TxDOT T221 Transition [11]

Figure M.2-3. Barrier Profile for Crash Tested Dowel Anchorage System

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no.

3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. In a TL-4 evaluation, a TxDOT 42-in. SSCB anchored by a 1-in. asphalt keyway was crash tested in accordance with MASH test designation no. 4-12 [10]. The reinforced, single-slope concrete barrier contained and redirected the 10000S vehicle with minimal system deflections and barrier damage. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [11].

Table M.2-2. Ohio Type D Anchorage Comparison

Evaluation Parameter		**OSSB-1 (TL-3)**	**TxDOT T221[(a)] 469689-2-2 (TL-3)**	**TxDOT SSCB 469467-3-1 (TL-4)**	**Ohio Type D Barrier**	
Anchorage	Type	Asphalt Keyway	#6 Dowels	Asphalt Keyway	#8 Dowels or Rebar	Asphalt Keyway
	Depth	1 in.	21 in. bar (Embed 6 in.)	1 in.	12 in. (Embed 6 in.)	1 in. with taper
	Spacing	Continuous	8 ft	Continuous	4 ft	Continuous
Geometry	Base Width	28⅜ in.	18 in.	24 in.	20 in.	
	Top Width	12 in.	10 in.	8 in.	12 in.	
	Height	43 in.	37 in.	42 in.	42 in.	
Reinf.	Longitudinal	--	10 x #5	14 x D18 WWR	--	
	Vertical	--	2 x #5 @ 12 in.	D9 WWR @ 8 in.	--	
Stability	Section Weight	904 plf	540 plf	700 plf	700 plf	
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	700 ft-lb	583 ft-lb	

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

The Type D barrier has similar geometry and anchorage details to the crash tested TxDOT T221 transition barrier, which was anchored by #6 dowels spaced at 8-ft intervals, with the dowels embedded 6-in. into the concrete pavement. The dowel bar anchorage configuration of the Type D barrier uses #8 dowels staggered at maximum 4-ft intervals. The larger bar size and tighter spacing mean that per unit length, the Type D barrier provides over three times the bar area of the TxDOT T221 transition. Therefore, the dowel bar anchorage is considered to have strength equal to or greater than the MASH TL-3 TxDOT T221 transition barrier anchorage.

The Type D barrier also had similar details to the test no. OSSB-1 and TxDOT SSCB barriers. In comparison to the two crash tested barriers, the Type D barrier has an equivalent height but narrower base width, and is, therefore, expected to possess less strength resistance than the crash tested systems. The keyway details are also not fully comparable: the traffic side of the Type D barrier provides a 1-in. deep asphalt keyway that is similar to the crash tested systems, but the non-traffic side is not detailed in kind. Finally, the unreinforced interior sections of the Type D barrier are not comparable to the reinforced TxDOT SSCB. Therefore, the asphalt keyway configuration of the Type D Roadside Barrier may provide adequate impact resistance, but without further research the strength and anchorage resistance cannot confidently be deemed crashworthy to MASH 2016 TL-4 or TL-3 standards.

Overall Evaluation

While the evaluation determined that barrier height and geometry met MASH TL-4 criteria, the computational strength evaluation indicated barrier end sections did not have adequate strength for MASH TL-3 or TL-4, and barrier strength could not be justified by comparison with existing crash tested systems. The evaluation of Ohio Type D Roadside Barrier is, therefore, inconclusive for MASH TL-3 and TL-4. The evaluation is summarized in Table M.2-3.

Table M.2-3. Ohio Type D Roadside Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 42 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="6">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>--</td><td rowspan="4">≥ 70 kips
Inconclusive</td><td rowspan="4">≥ 80 kips
Inconclusive</td></tr>
<tr><td>End</td><td>51 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>323 kips</td></tr>
<tr><td>End</td><td>253 kips</td></tr>
<tr><td rowspan="2">Anchorage</td><td colspan="2">1-in. Asphalt Keyway</td><td>Inconclusive</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Staggered #8 Dowel Bars</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Inconclusive</td></tr>
</table>

M.2.1 References

1. *Single Slope Barrier, Type D, RM-4.3*, Office of Roadway Engineering, State of Ohio Department of Transportation, July 21, 2017.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

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7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

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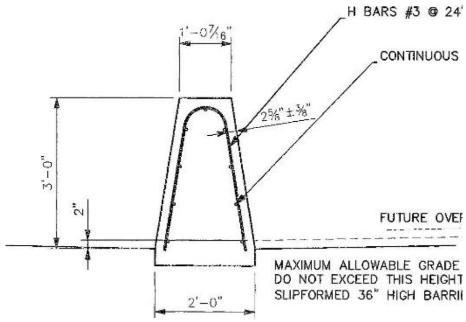
10. Bligh, R.P., Menges, W.L., Kuhn, D.L., *MASH Evaluation of TxDOT Roadside Safety Features-Phase I*, FHWA/TX-17/0-6946-1, Texas Transportation Institute, College Station, TX, January 2018.

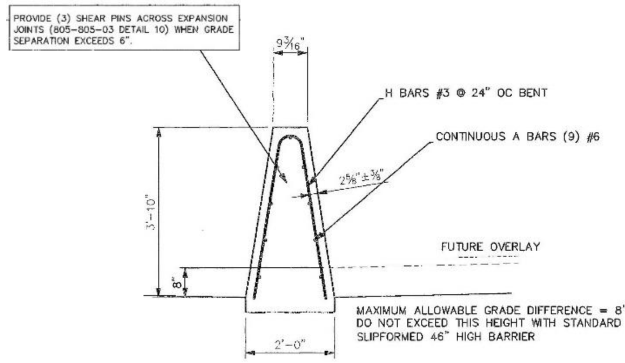
11. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

Appendix N. South Carolina Permanent Concrete Barrier MASH Evaluations

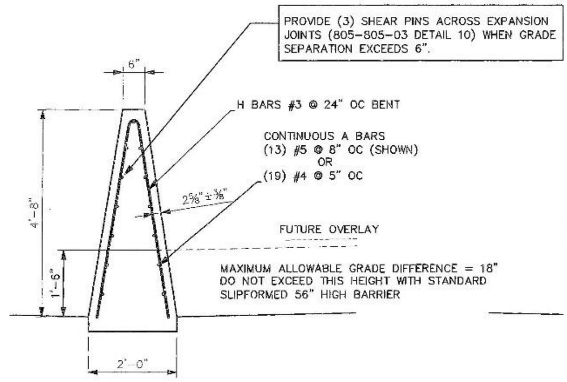
N.1. MASH Equivalency of the South Carolina DOT Type 36SS, 46SS, and 56SS Barriers



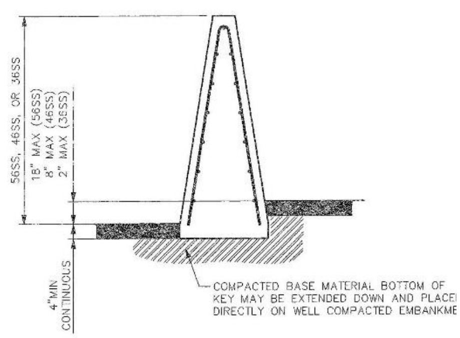
Type 36SS Barrier



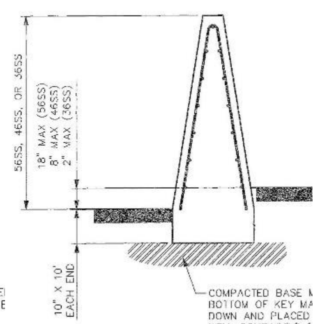
Type 46SS Barrier



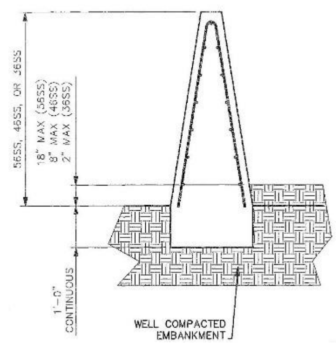
Type 56SS Barrier



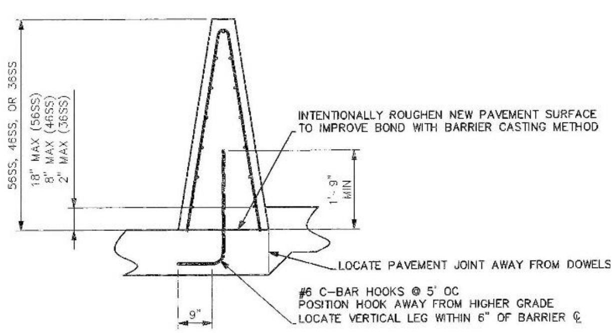
(a) 4-in. Keyway



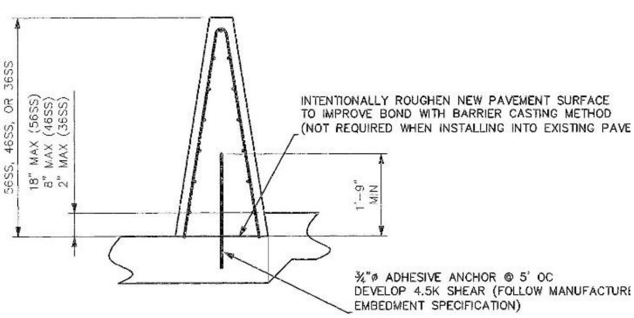
(b) End Anchor Footing



(c) Continuous Footing



(d) #6 Hooked Bars



(e) #6 Straight Bars

Figure N.1-1. South Carolina DOT Type 36SS, 46SS and 56SS with Anchorage Alternatives [1]

Overview and Stability Evaluation

The South Carolina DOT Type 36SS, 46SS and 56SS are a series of single-slope barriers with a base width of 24 in. and heights of 36 in., 46 in., and 56 in., respectively. The barriers have a 9.1-degree single-slope traffic face. Vertical reinforcement consists of #3 bent bars spaced at 24 in. Longitudinal reinforcement is distributed around the perimeter of each barrier. The Type 36SS and Type 46SS use nine #6 bars. The Type 56SS uses either thirteen #5 bars or nineteen #4 bars.

The South Carolina standard details provide five anchorage configurations for the barrier series: (a) 4-in. continuous rigid or flexible pavement keyway, (b) a 10-in. deep by 10-ft long concrete footing end anchorage, (c) a 12-in. deep continuous monolithic footing, (d) #6 hooked bars embedded in the concrete deck and spaced at 5 in., and (e) #6 straight bars epoxied into concrete deck and spaced at 5 in. In the bar anchorage options the bar must extend a minimum of 21 in. into the barrier. Design details for all barrier configurations are shown in Figure N.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the Type 36SS, 46SS and 56SS barriers have the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) and shown in Table N.1-1 The TL-4 design loads include separate cases for barrier heights equal to 36 in. and greater than 36 in. The Type 36SS barrier was evaluated for a 70-kip design load distributed over a 4-ft length. The Type 46SS and 56SS barriers were evaluated for an 80-kip design load distributed over a 5 ft length. Additionally, a punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. The results of the computational analysis are summarized in Table N.1-2.

Table N.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

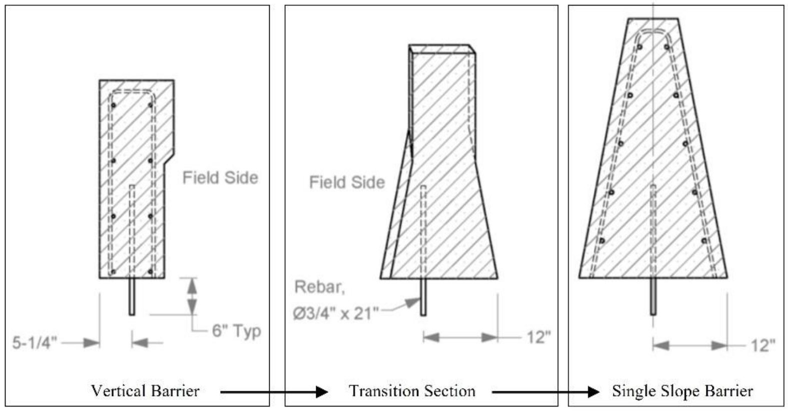
Table N.1-2. Computational Analysis Results for Type 36SS, 46SS, and 56SS Barriers

Barrier	Design Load	Yield Line Analysis		Punching Shear Analysis	
		Interior Section	End Section	Interior Section	End Section
36SS	70 kips	127 kips	114 kips	273 kips	209 kips
46SS	80 kips	111 kips	101 kips	269 kips	214 kips
56SS	80 kips	104 kips	96 kips	273 kips	214 kips

The results of the computational analyses indicate that the Type 36SS, 46SS, and 56SS all satisfy MASH TL-4 loading criteria for interior and end sections. Based on the favorable computational results, it is believed that the anchorage configurations with embedded and epoxied bars would be crashworthy to MASH 2016 TL-4. However, the pavement keyway, end anchorage footing, and continuous footing details required further investigation to justify crashworthiness to MASH 2016. Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of these anchorage configurations.

Direct Comparison – Cast-In Hooked or Epoxied #6 Bars

Crash testing has been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. The transition was anchored by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety criteria of MASH test designation no. 3-21 [10]. The profiles of the crash tested system is shown in Figure N.1-2 and a comparison with the Type 36SS, 46SS, and 56SS barriers is provided in Table N.1-3.



TxDOT T221 Transition

Figure N.1-2. TxDOT T221 Transition Barrier Profiles [10]

Table N.1-3. South Carolina Type 36SS, 46SS, and 54A Anchorage Comparison

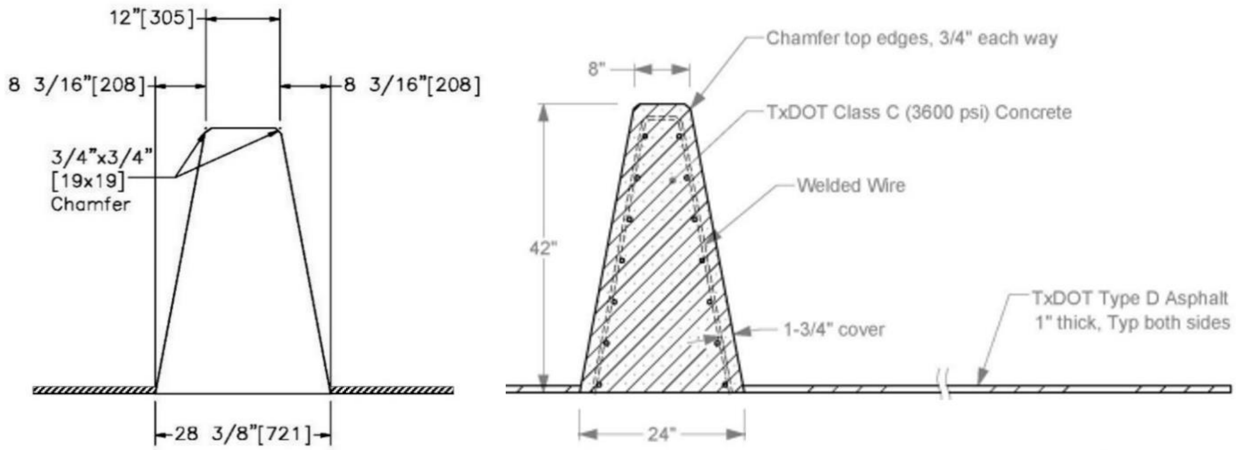
Evaluation Parameter		**TxDOT T221 469689-2-2 (TL-3)** [(a)]	**South Carolina Single-Slope**		
			36SS	**46SS**	**56SS**
Barrier Shape		Transition: Single-Slope and Vertical	Single Slope		
Anchorage	Type	#6 Dowels	#6 Dowels		
	Depth	21 in. bar (Embed 6 in.)	Hooked or Epoxy Embeded		
	Spacing	8 ft	5 ft		
Geometry	Base Width	18 in.	24 in.		
	Top Width	10 in.	12$\frac{7}{16}$ in.	9$\frac{3}{16}$ in.	6 in.
	Height	37 in.	36 in.	46 in.	56 in.
Reinf.	Longitudinal	10 x #5	9 x #6	9 x #6	13 x #5 or 19 x #4
	Vertical	#5 @ 12 in.	#3 @ 24 in.		
Stability	Section Weight	540 plf	683 plf	795 plf	875 plf
	Overturning Stability per ft	405 ft-lb	683 ft-lb	795 ft-lb	875 ft-lb

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

As shown in Table H.1-3, the TxDOT T221 transition was anchored by #6 dowel bars spaced at 8-ft intervals. The South Carolina DOT barriers were anchored by #6 dowel bars spaced at 5-ft intervals. Due to the tighter dowel spacing, the Type 36SS, 46SS, and 56SS barriers were considered to have anchorage strengths equal to or greater than the MASH TL-3 TxDOT T221 transition barrier. Unfortunately, a similar barrier has not yet been crash tested to MASH TL-4, so the anchorage strength of the South Carolina barriers is indeterminant for MASH TL-4.

Direct Comparison – Pavement Keyway Alternative

The South Carolina DOT standard plans provide anchorage details for a 4-in. pavement keyway. Existing research on keyway-anchored permanent concrete barriers is limited, but two crash tests have been conducted on 42-in. tall single-slope concrete barriers with asphalt keyway anchorages. The barrier profiles for the two crash tested systems are shown in Figure N.1-3.



Test No. OSSB-1 TxDOT 42-in. SSCB

Figure N.1-3. Barrier Profiles for Test Nos. OSSB-1 [6] and 469467-3-1 (TxDOT 42-in. SSCB) [11]

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. In a TL-4 evaluation, a TxDOT 42-in. SSCB anchored by a 1-in. asphalt keyway was crash tested in accordance with MASH test designation no. 4-12 [11]. The reinforced, single-slope concrete barrier contained and redirected the 10000S vehicle with minimal system deflections and barrier damage. A comparison of the two crash tested systems with the Type 346SS 46SS and 56SS barriers is provided in Table L.2-3.

Table N.1-4. South Carolina Type 36SS, 46SS and 56SS Asphalt Keyway Comparison

Evaluation Parameter		**OSSB-1 (TL-3)**	**TxDOT SSCB 469467-3-1 (TL-4)**	**South Carolina Single-Slope**		
				36SS	**46SS**	**56SS**
Asphalt Keyway Depth		1 in.	1 in.	4 in.		
Geometry	Base Width	$28\frac{3}{8}$ in.	24 in.	24 in.		
	Top Width	12 in.	8 in.	$12\frac{7}{16}$ in.	$9\frac{3}{16}$ in.	6 in.
	Height	43 in.	42 in.	36 in.	46 in.	56 in.
Reinf.	Longitudinal	--	14 x D18 WWR	9 x #6	9 x #6	13 x #5 or 19 x #4
	Vertical	--	D9 WWR @ 8 in.	#3 @ 24 in.		
Stability	Section Weight	904 plf	700 plf	683 plf	795 plf	875 plf
	Overturning Stability per ft	1068 ft-lb	700 ft-lb	683 ft-lb	795 ft-lb	875 ft-lb

The Type 36SS, 46SS and 56SS barriers specify a 4-in. asphalt keyway versus the 1-in. keyway in the tested systems, which is anticipated to increase the anchorage strength compared to the tested systems. Additionally, all the South Carolina barriers provide significant reinforcement and have the same base width as the TL-4 tested TxDOT SSCB system. Therefore, the Type 36SS, 46SS, and 56SS barriers are expected to be crashworthy to MASH TL-4 when configured with a 4-in. asphalt keyway. The standard details also permit the use of a 4-in concrete pavement keyway. This detail is anticipated to provide equal or greater strength than the asphalt keyway and is also considered crashworthy to TL-4.

Direct Comparison – End Anchorage Footing Alternative

The South Carolina DOT standard plans provide anchorage details for a 10-in. deep by 10-ft long unreinforced concrete footing. Only one known crash test has been conducted on a barrier with an end anchorage footing. The California Type 60 barrier, a 36-in. tall single-slope reinforced concrete barrier anchored by 10-in. deep by 10-ft long footings, was crash tested with the 1100C vehicle and met the performance criteria of MASH test designation no. 3-10 [8]. However, without a 2270P crash test or TL-4 crash test data, it is difficult to determine the system behavior at higher impact severities. Therefore, without additional research or crash testing, the evaluation of the end anchorage footing system remains inconclusive for both MASH TL-3 and TL-4.

Direct Comparison – Continuous Footing Alternative

The South Carolina DOT standard plans provide anchorage details for a 12-in. deep continuous, monolithic footing. Currently, no computational methods exist for the analysis of this type of anchorage system. However, standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [12], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [13]. The details of these crashworthy barriers are compared to the foundation details of the Type 36SS, 46SS, and 56SS in Table N.1-5 and a schematic comparison is shown in Figure N.1-4.

Table N.1-5. South Carolina Type 36SS, 46SS and 56SS Footing Comparison

Test Level	Test	Barrier Height	Base Width	Depth	Segment Length	Ditch Slope	Ditch Offset
TL-4	FE-1	36 in.	16 in.	33 in.	30 ft	1V:2H	1 ft
TL-4	FE-2	36 in.	18 in.	27 in.	50 ft	N/A	N/A
TL-4	FE-3	36 in.	13 in.	10 in.	50 ft	N/A	N/A
TL-3	CT	32 in.	24 in. (a)	10 in.	20 ft	1.5V:2H	2 ft
SC Type 36SS		36 in.	24 in.	12 in.	Unspecified	Unspecified	N/A
SC Type 46SS		46 in.	24 in.	12 in.	Unspecified	Unspecified	N/A
SC Type 56SS		56 in.	24 in.	12 in.	Unspecified	Unspecified	N/A

N/A – Not Applicable, FE –Finite Element Analysis, CT – Crash Test
(a) Foundation is battered to match slope of barrier.

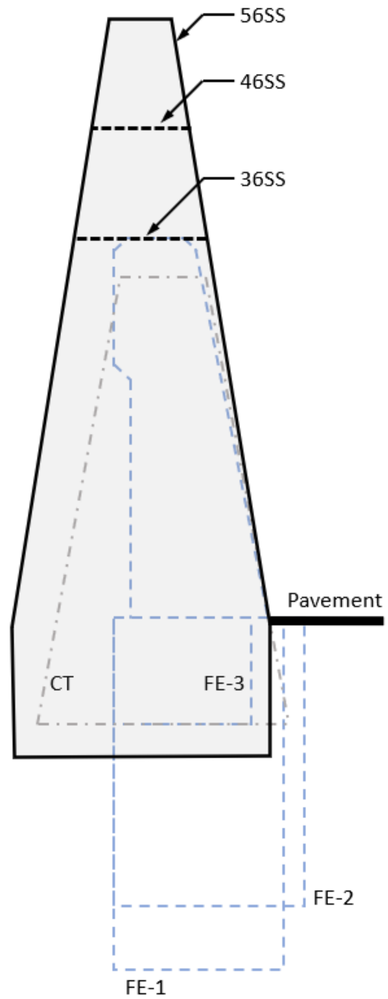


Figure N.1-4. Type 36SS, 46SS, and 56SS Geometry Comparison

The simulations conducted on concrete barriers with standalone beam foundations resulted in minimal system displacement, and the 10000S test vehicle was successfully contained and redirected according to MASH TL-4. The Type 36SS, 46SS, and 56SS 12-in. deep continuous footing has a similar depth to the system in simulation FE-3 and a larger width than any of the simulated foundations. The increased width is expected to increase the strength compared to the simulated system. Because simulation FE-3 forms the basis of the justification, this MASH evaluation applies to systems with segment lengths of at least 50 ft.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the South Carolina Type 36SS, 46SS and 56SS barriers are believed to be crashworthy and in compliance with MASH TL-4 for the following anchorage configurations detailed in the South Carolina standard plans: 4-in. keyway, #6 hooked bars, #6 epoxied bars, and 12-in. deep continuous footing with minimum 50-ft segment lengths. Current research and crash testing are insufficient to justify the crashworthiness of the end anchorage footing configuration. The barrier evaluation is summarized in Tables N.1-6 through N.1-8

Table N.1-6. South Carolina Type 36SS Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 36 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="8">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>127 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 70 kips
Pass</td></tr>
<tr><td>End</td><td>114 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>273 kips</td></tr>
<tr><td>End</td><td>209 kips</td></tr>
<tr><td rowspan="4">Anchorage</td><td colspan="2">4-in. Pavement Keyway</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="2">End Anchor Footing</td><td>Inconclusive</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Continuous Footing</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="2">Cast-In Hooked or Epoxied #6 Bars</td><td>Pass</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass for Some Configurations</td><td>Pass for Some Configurations</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

Table N.1-7. South Carolina Type 46SS Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 46 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	111 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	101 kips		
	Punching Shear	Interior	269 kips		
		End	214 kips		
	Anchorage	4-in. Pavement Keyway		Pass*	Pass*
		End Anchor Footing		Inconclusive	Inconclusive
		Continuous Footing		Pass*	Pass*
		Cast-In Hooked or Epoxied #6 Bars		Pass	Inconclusive
Overall MASH Evaluation				Pass for Some Configurations	Pass for Some Configurations

* Justified based on available crash tests or finite element simulations.

Table N.1-8. South Carolina Type 56SS Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 56 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	104 kips	≥ 70 kips Pass	≥ 80 kips Pass
		End	96 kips		
	Punching Shear	Interior	273 kips		
		End	214 kips		
	Anchorage	4-in. Pavement Keyway		Pass*	Pass*
		End Anchor Footing		Inconclusive	Inconclusive
		Continuous Footing		Pass*	Pass*
		Cast-In Hooked or Epoxied #6 Bars		Pass	Inconclusive
Overall MASH Evaluation				Pass for Some Configurations	Pass for Some Configurations

* Justified based on available crash tests or finite element simulations.

N.1.1 References

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

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12. Sheikh, N.M., Bligh, R.P., Kovar, J.C., Cakalli, S., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of Structurally Independent Foundations for 36-inch Tall Single-Slope Traffic Rail (SSTR) for MASH TL-4*, FHWA/TX-19/0-6968-R7, Texas Transportation Institute, College Station, TX, October 2019.

13. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

Appendix O. South Dakota Permanent Concrete Barrier MASH Evaluations

O.1. MASH Equivalency of South Dakota DOT Retrofit Bridge Rail

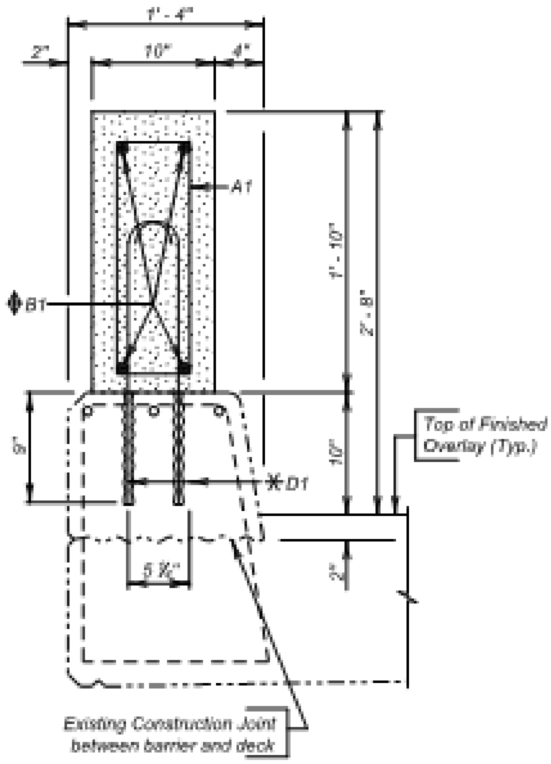

Figure O.1-1. South Dakota DOT Retrofit Bridge Rail Details [1]

Overview and Stability Evaluation

The South Dakota DOT Retrofit Bridge Rail is a 22-in. tall, vertical reinforced concrete barrier with a 10-in. parapet for a total height of 32 in. The retrofit has a 10-in. top width, and due to the lower parapet, has a traffic face similar to a New Jersey barrier. The retrofit barrier is vertically reinforced with #4 stirrups spaced at 18-in. and is anchored to the existing parapet with vertical #6 bars spaced at 18 in. on the traffic side and 36 in. on the non-traffic side. Longitudinal reinforcement in the retrofit barrier consists of seven #4 bars. The parapet was assumed to be anchored to the deck by vertical #4 stirrups spaced at 18 in. based on the spacing of the retrofit barrier anchorage to the existing parapet. Design details for the retrofit barrier are shown in Figure O.1-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that TL-3 concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. However, New Jersey and F-shape barriers have only been constructed at a minimum height of 32 in. Therefore, for TL-3 impacts, New Jersey and F-shape barriers must provide a minimum height of 32 in. Thus, the 32-in. tall South Dakota Retrofit Bridge Rail has the required height to contain MASH TL-3 impact conditions.

Shape Evaluation

The retrofit barrier traffic face has characteristics of the New Jersey and vertical geometries, which have met MASH TL-3 performance criteria in crash tests with the 1100C and 2270P vehicles [4–6]. The tested barriers had heights of 32 or 34 in. Thus, the face geometry of the retrofit barrier has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [7], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2) [3]. As seen in Table G.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length. Thus, 4 ft was utilized as the L_t term in the yield line equations. A punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table O.1-1. Effective Loads for Design of MASH Barriers [8]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis of the retrofit concrete barrier was conducted on the full barrier section as well as the upper section of the barrier. The full section had a strength of 87 kips for interior sections and 48 kips for end sections adjacent to discontinuities (expansion gaps and joints). Additionally, the upper section of the barrier had interior and end section strengths of 80 kips and 64 kips, respectively. The punching shear capacity of the barrier was at the interior and end sections was 151 kips and 118 kips, respectively. The end section yield line was below the required 70 kips. Therefore, the barrier satisfies MASH TL-3 loading criteria for interior sections but does not have sufficient capacity at end sections.

Overall Evaluation

While the evaluation determined that barrier height and geometry met MASH TL-3 criteria, the computational evaluation of strength and anchorage indicated barrier end sections did not have adequate strength. Therefore, as summarized in Table O.1-2, the TL-3 evaluation of the barrier is inconclusive.

Table O.1-2. South Dakota Retrofit Bridge Rail Evaluation Summary

<table>
<tr><th rowspan="2" colspan="2">Criteria</th><th rowspan="2" colspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 32 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Other</td><td>Pass</td><td rowspan="6">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>80 kips</td><td rowspan="4">≥ 70 kips
Inconclusive</td></tr>
<tr><td>End</td><td>48 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>151 kips</td></tr>
<tr><td>End</td><td>118 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">Reinforcement</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Inconclusive</td><td>Fail</td></tr>
</table>

O.1.1 References

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Appendix P. Utah Permanent Concrete Barrier MASH Evaluations

P.1. MASH Equivalency of Utah DOT 42-in. Constant Slope Concrete Median Barrier

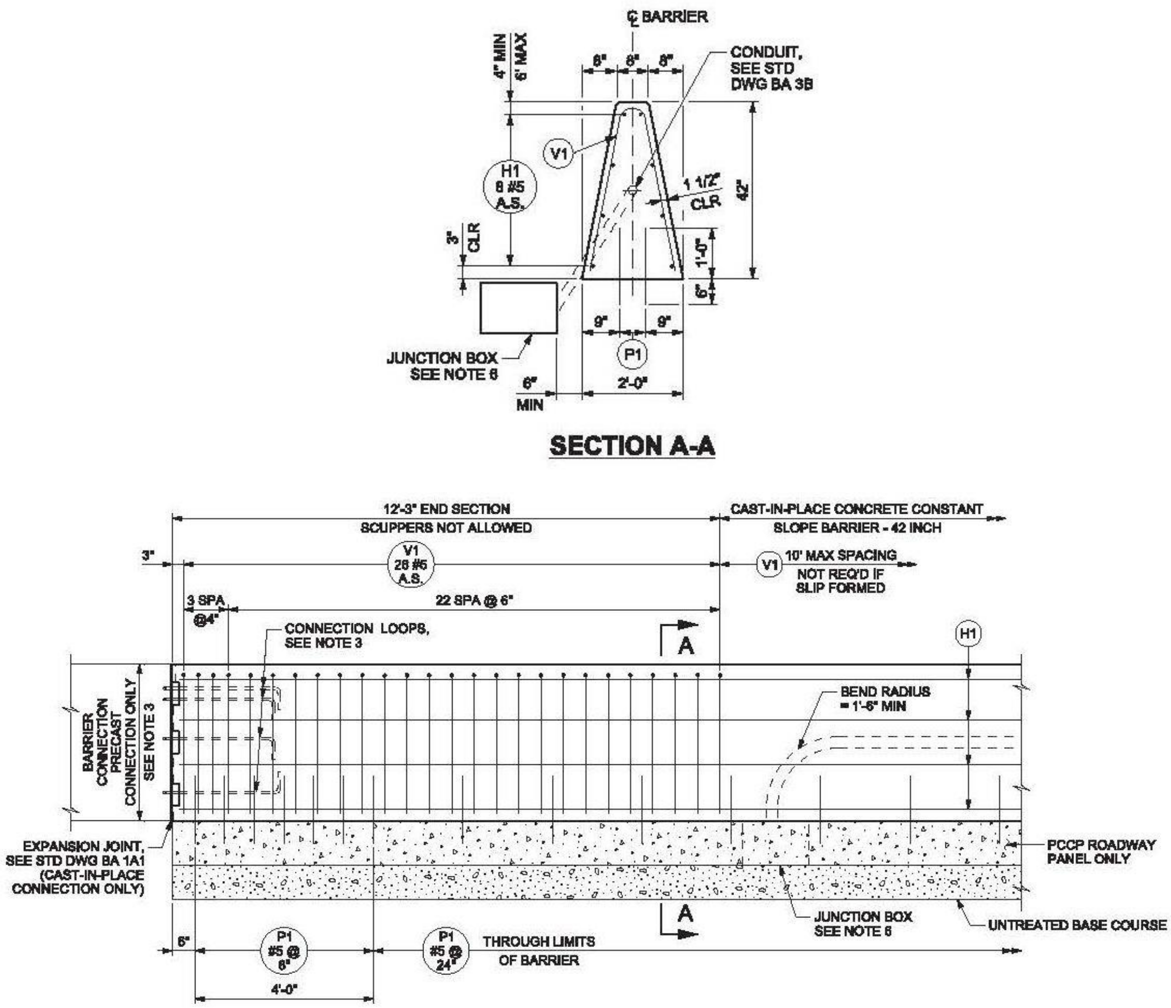


Figure P.1-1. Utah 42-in. Constant Slope Barrier Details [1]

Overview and Stability Evaluation

The Utah DOT Constant Slope Concrete Median Barrier is a 42-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face. Vertical reinforcement consists of #5 bent bars spaced at a maximum of 10 ft. However, the vertical bars may be omitted at interior barrier sections if the barrier is slip formed. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier. Anchorage is provided by #5 bars spaced at 24 in. and embedded 6 in. into the concrete pavement. Design details for the 42-in. Constant Slope Barrier are shown in Figure P.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no.

4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall, Constant Slope Median Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table P.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Because interior sections had minimal vertical reinforcement, only the end sections could be evaluated by yield line analysis A punching shear analysis was conducted for interior and end sections in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table P.1-1. Effective Loads for Design of MASH Barriers [3]

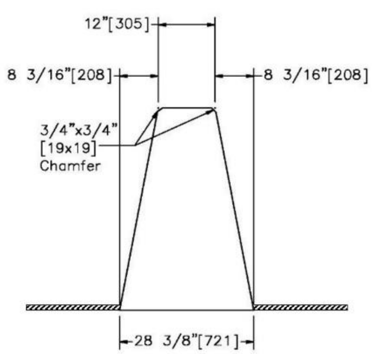
Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 172 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier at interior and end sections was 274 kips and 225 kips, respectively. Therefore, the 42-in. single-slope barrier satisfies MASH TL-4 loading criteria for end sections, but without a yield line analysis, the strength of the interior sections remains inconclusive.

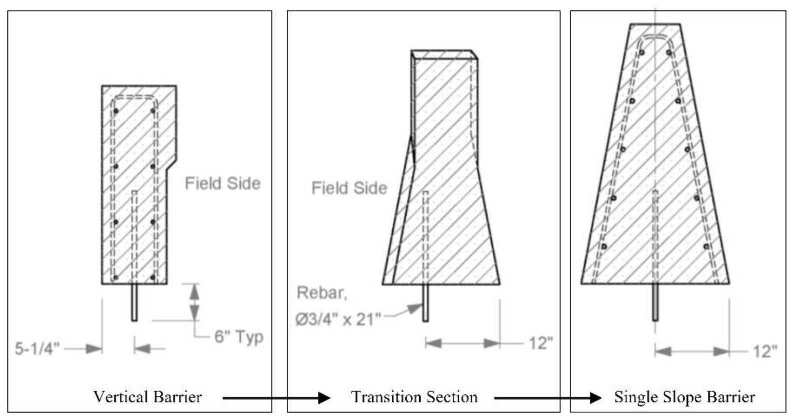
Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the 42-in. Constant Slope Barrier. Currently, no crash tests have been performed on barriers with only longitudinal reinforcement, but an unreinforced single-slope barrier with asphalt keyway anchorage [6] and a reinforced concrete barrier with dowel anchorage [10] have been crash tested to MASH TL-3.

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [10]. The profiles of the crash tested systems are shown in Figure P.1-2 and a comparison with the Type C Median Barrier is provided in Table P.1-2.



Test No. OSSB-1



TxDOT T221 Transition

Figure P.1-2. Test No. OSSB-1 Barrier [6] and TxDOT T221 Transition Barrier [10] Profiles

Table P.1-2. Utah 42-in. Single-Slope Median Barrier Anchorage Comparison

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT T221 [(a)] 469689-2-2 (TL-3)	Utah 42-in. Constant Slope
Anchorage	Type	Asphalt Keyway	1 x #6 Dowels	2 x #5 Dowels
	Depth	1 in.	21 in. bar (Embed 6 in.)	18 in. bar (Embed 6 in.)
	Spacing	Continuous	8 ft	2 ft
Geometry	Base Width	28⅜ in.	18 in.	24 in.
	Top Width	12 in.	10 in.	8 in.
	Height	43 in.	37 in.	42 in.
Reinforcement	Longitudinal	--	10 x #5	8 x #5
	Vertical	--	2 x #5 @ 12 in.	--
Stability	Section Weight	904 plf	540 plf	700 plf
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	700 ft-lb

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

Compared to the test no. OSSB-1 barrier, the 42-in. Constant Slope Barrier had similar overall geometry but was 4 in. narrower. However, the #5 longitudinal reinforcement in the Constant Slope Barrier would provide increased strength compared to the unreinforced barrier. Therefore, the 42-in. Constant Slope Barrier was considered to have a strength equal to or greater than the unreinforced MASH TL-3 barrier evaluated in test no. OSSB-1. Additionally, as part of the research associated with test no. OSSB-1, the 1-in. asphalt keyway anchorage was deemed a critically weak anchorage configuration. Therefore, the dowel bar anchorage used in the Constant Slope Barrier is expected to provide higher anchorage strength than the asphalt keyway used in test no. OSSB-1.

The TxDOT T221 transition was anchored by single #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The 42-in. Constant Slope Barrier uses two #5 bars spaced at 2-ft intervals and embedded 6 in. The tighter spacing means that per unit length, the Constant Slope Barrier provides five times the bar area of the TxDOT T221 transition. Therefore, the 42-in. Constant Slope Barrier is considered to have anchorage strength equal to or greater than the MASH TL-3 TxDOT T221 transition barrier.

Unfortunately, the test no. OSSB-1 and TxDOT T221 transition barrier systems were only evaluated to MASH TL-3 criteria. There is no known TL-4 crash testing of comparable barriers. Thus, the MASH TL-4 evaluation of the 42-in. Constant Slope Barrier remains inconclusive until further testing or evaluation is conducted.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Utah DOT 42-in. Constant Slope Concrete Median Barrier is believed to be crashworthy and in compliance with MASH TL-3 when anchored with the specified dowel bar anchorage. The barrier may also be crashworthy and in compliance with MASH TL-4, but the minimal vertical reinforcement makes it difficult to qualify barrier strength and anchorage. The evaluation of the barrier at MASH TL-4 was, therefore, inconclusive. The barrier evaluation is summarized in Table P.1-3.

Table P.1-3. Utah 42-in. Constant Slope Concrete Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 42 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>--</td><td rowspan="4">≥ 70 kips
Pass*</td><td rowspan="4">≥ 80 kips
Inconclusive</td></tr>
<tr><td>End</td><td>172 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>274 kips</td></tr>
<tr><td>End</td><td>225 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">#5 Reinforcing Bars</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

P.1.1 References

1. Cast-in-Place Concrete Constant Slope Barrier – 42 inch, TL-3, Page 1 of 8, Standard Drawing Number BA 3A1, Utah Department of Transportation, Salt Lake City, UT, August 2020.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.

7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.

9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

10. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

P.2. MASH Equivalency of Utah DOT 42-in. Half Constant Slope Concrete Barrier

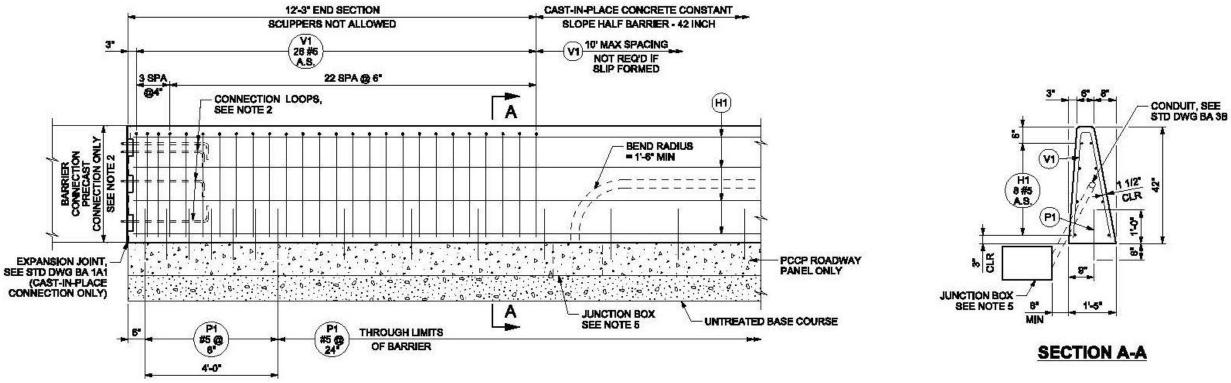


Figure P.2-1. Utah 42-in. Half Constant Slope Concrete Barrier [1]

Overview and Stability Evaluation

The Utah DOT 42-in. Half Constant Slope Concrete Barrier is a 42-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face. Vertical reinforcement consists of #5 bent bars spaced at a maximum of 10 ft. However, the vertical bars may be omitted at interior barrier sections if the barrier is slip formed. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier. Anchorage is provided by #5 bars spaced at 24 in. and embedded 6 in. into the concrete pavement. Design details for the 42 in. barrier are shown in Figure P.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall, Half Constant Slope Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table P.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Because interior sections had minimal vertical reinforcement, only the end sections could be evaluated by yield line analysis A punching shear analysis was conducted for interior and end sections in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table P.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

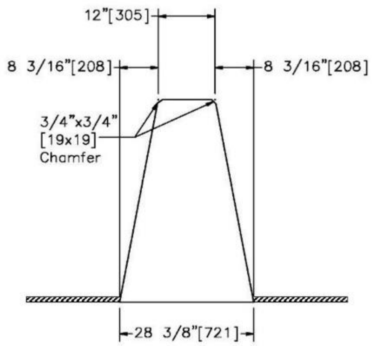
Yield line analysis determined barrier strength to be 108 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier at interior and end sections was 156 kips and 129 kips, respectively. Therefore, the 42-in. Half Constant Slope Barrier satisfies MASH TL-4 loading criteria for end sections, but without a yield line analysis, the strength of the interior sections is inconclusive by computational methods.

Direct Comparison of Strength and Anchorage

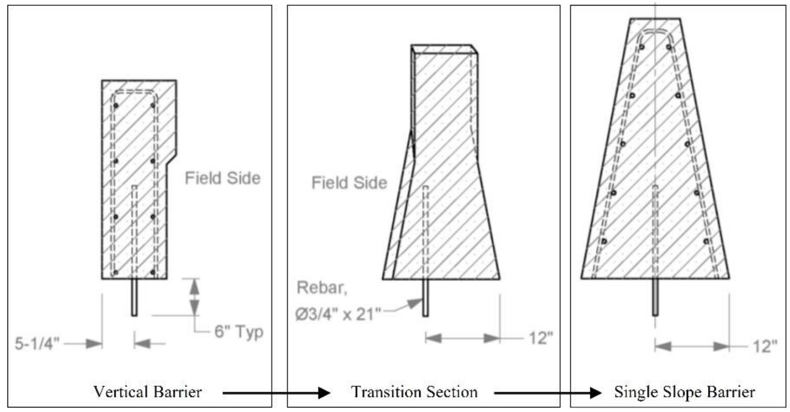
Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the 42-in. Constant Slope Barrier. Currently, no crash tests have been performed on barriers with only longitudinal reinforcement. However, an unreinforced single-slope barrier with asphalt keyway anchorage [6] and a reinforced concrete barrier with dowel anchorage [10] have been crash tested to MASH TL-3.

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21

[10]. The profiles of the crash tested systems are shown in Figure P.2-2 and a comparison with the Half Constant Slope Barrier is provided in Table P.2-2.



Test No. OSSB-1



TxDOT T221 Transition

Figure P.2-2. Test No. OSSB-1 Barrier [6] and TxDOT T221 Transition Barrier [10] Profiles

Table P.2-2. Utah 42-in. Half Constant Slope Concrete Barrier Anchorage Comparison

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT T221 (a) 469689-2-2 (TL-3)	Utah 42-in. Half Constant Slope
Anchorage	Type	Asphalt Keyway	1 x #6 Dowels	2 x #5 Dowels
	Depth	1 in.	21 in. bar (Embed 6 in.)	18 in. bar (Embed 6 in.)
	Spacing	Continuous	8 ft	2 ft
Geometry	Base Width	28⅜ in.	18 in.	17 in.
	Top Width	12 in.	10 in.	6 in.
	Height	43 in.	37 in.	42 in.
Reinforcement	Longitudinal	--	10 x #5	8 x #5
	Vertical	--	2 x #5 @ 12 in.	--
Stability	Section Weight	904 plf	540 plf	503 plf
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	377 ft-lb

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

The 42-in. Half Constant Slope Barrier had similarities with the TL-3 crash tested TxDOT T221 transition barrier dowel-anchored system. The TxDOT T221 transition was anchored by single #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The Half Constant Slope Barrier uses two #5 bars spaced at 2-ft intervals and embedded 6 in. The tighter spacing means that per unit length, the Half Constant Slope Barrier provides five times the bar area of the TxDOT T221 transition. However, the Half Constant Slope Barrier is also taller, narrower, lighter, and more lightly reinforced than the TxDOT T221 transition barrier. While the dowel bar area comparison is favorable, these other factors make it difficult to qualify barrier strength and anchorage by direct comparison. Similarly, while the longitudinal reinforcing in the Half Constant Slope Barrier would increase strength in comparison to the unreinforced concrete of the barrier in test no. OSSB-1, the crash tested barrier was significantly larger than the Half Constant Slope Barrier, preventing qualification by direct comparison. From the existing body of research and crash test data, the evaluation of the Half Constant Slope Barrier strength and anchorage remains inconclusive.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Utah 42-in. Half Constant Slope Concrete Barrier may be crashworthy to MASH TL-3 or TL-4, but the minimal vertical reinforcement makes it difficult to qualify barrier strength and anchorage. The evaluation of the barriers at MASH TL-3 and TL-4 was, therefore, inconclusive. The barrier evaluation is summarized in Table P.2-3.

Table P.2-3. Utah 42-in. Half Constant Slope Concrete Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Inconclusive	≥ 80 kips Inconclusive
		End	108 kips		
	Punching Shear	Interior	156 kips		
		End	129 kips		
	Anchorage	#5 Reinforcing Bars		Inconclusive	Inconclusive
Overall MASH Evaluation				Inconclusive	Inconclusive

P.2.1 References

1. *Cast-in-Place Concrete Constant Slope Half Barrier – 42 inch*, Utah Department of Transportation, Salt Lake City, UT, August 2020.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.
4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
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6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.
7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
8. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
10. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

P.3. MASH Equivalency of Utah DOT 54-in. Constant Slope Concrete Median Barrier

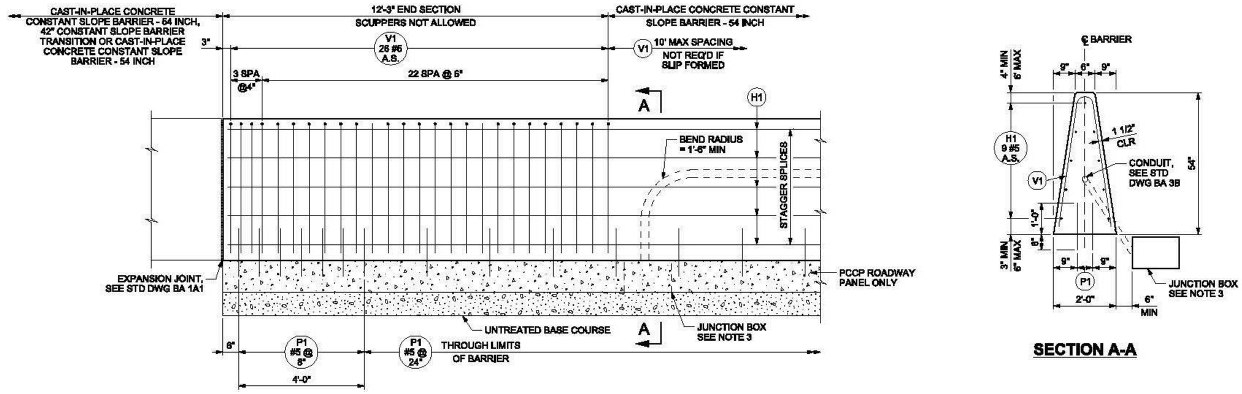


Figure P.3-1. Utah 54-in. Constant Slope Concrete Median Barrier [1]

Overview and Stability Evaluation

The Utah DOT Single-Slope Concrete Median Barrier is a 54-in. tall reinforced concrete barrier with a 9.5-degree single-slope traffic face. Vertical reinforcement consists of #5 bent bars spaced at a maximum of 10 ft. However, the vertical bars may be omitted at interior barrier sections if the barrier is slip formed. Longitudinal reinforcement is provided by four #5 bars on both the front and back sides of the barrier, with an additional #5 bar at the top of the section. Anchorage is provided by #5 bars spaced at 24 in. and embedded 6 in. into the concrete pavement. Design details for the 54-in. Constant Slope Median Barrier are shown in Figure P.3-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 54-in. tall, Constant Slope Median Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table P.3-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. Because interior sections had minimal vertical reinforcement, only the end sections could be evaluated by yield line analysis A punching shear analysis was conducted for interior and end sections in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table P.3-1. Effective Loads for Design of MASH Barriers [3]

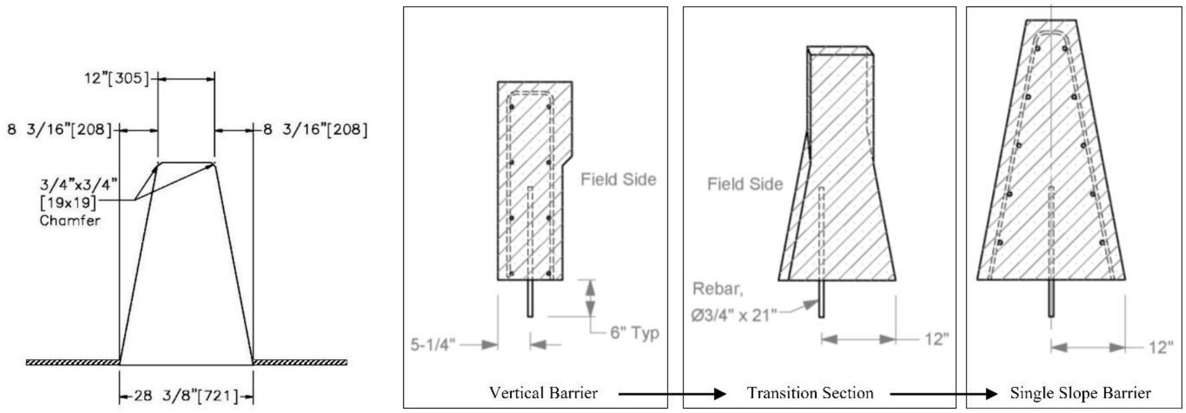
Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 192 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier at interior and end sections was 333 kips and 262 kips, respectively. Therefore, the barrier satisfies MASH TL-4 loading criteria for end sections, but without a yield line analysis, the strength of the interior sections is inconclusive by computational methods.

Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the 54-in. Constant Slope Barrier. Currently, no crash tests have been performed on barriers with only longitudinal reinforcement. However, an unreinforced single-slope barrier with asphalt keyway anchorage [6] and a reinforced concrete barrier with dowel anchorage [10] have been crash tested to MASH TL-3.

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [6]. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [10]. The profiles of the crash tested systems are shown in Figure P.3-2 and a comparison with the 54-in. Median Barrier is provided in Table P.3-2.



Test No. OSSB-1 TxDOT T221 Transition

Figure P.3-2. Test No. OSSB-1 Barrier [6] and TxDOT T221 Transition Barrier [10] Profiles

Table P.3-2. Utah 54-in. Constant Slope Concrete Median Barrier Anchorage Comparison

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT T221 (a) 469689-2-2 (TL-3)	Utah 54-in. Median Barrier
Anchorage	Type	Asphalt Keyway	1 x #6 Dowels	2 x #5 Rebar
	Depth	1 in.	21 in. bar (Embed 6 in.)	18 in. bar (Embed 6 in.)
	Spacing	Continuous	8 ft	2 ft
Geometry	Base Width	28⅜ in.	18 in.	24 in.
	Top Width	12 in.	10 in.	6 in.
	Height	43 in.	37 in.	54 in.
Reinforcement	Longitudinal	--	10 x #5	9 x #5
	Vertical	--	2 x #5 @ 12 in.	--
Stability	Section Weight	904 plf	540 plf	843 plf
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	843 ft-lb

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

The 54-in. Median Barrier had similarities with the TL-3 crash tested TxDOT T221 transition barrier dowel-anchored system. The TxDOT T221 transition was anchored by single #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The 54-in. Median Barrier uses two #5 bars spaced at 2-ft intervals and embedded 6 in. The tighter spacing means that per unit length, the 54-in. Median Barrier provides five times the bar area of the TxDOT T221 transition. The 54-in. Median Barrier is taller and more lightly reinforced than the TxDOT

T221 transition barrier, but the impact on strength and overturning stability is expected to be offset by the larger cross section and much larger section weight. The height and section weight of the barrier in test no. OSSB-1 were similar to the 54-in. Median Barrier. As part of the research associated with test no. OSSB-1, the 1-in. asphalt keyway anchorage was deemed a critically weak anchorage configuration. Therefore, the 54-in. Median Barrier is considered to have strength equal to or greater than the MASH TL-3 TxDOT T221 transition and test no. OSSB-1 barriers.

Unfortunately, while the TxDOT T221 transition and test no. OSSB-1 barrier systems provided information on the crashworthiness of unreinforced barriers and dowel-bar anchorages, the systems were only evaluated to MASH TL-3 criteria. There is no known TL-4 crash testing of comparable barriers. Thus, the MASH TL-4 evaluation of the 54-in. Median Barrier remains inconclusive until further testing or evaluation is conducted.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Utah DOT 54-in. Constant Slope Concrete Median Barrier is believed to be crashworthy and in compliance with MASH TL-3 when anchored with the specified rebar anchorage. The barrier may also be crashworthy and in compliance with MASH TL-4, but the minimal vertical reinforcement makes it difficult to qualify barrier strength and anchorage. The evaluation of the barrier at MASH TL-4 was, therefore, inconclusive. The barrier evaluation is summarized in Table P.3-3.

Table P.3-3. Utah 54-in. Constant Slope Concrete Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 54 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="5">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>--</td><td rowspan="4">≥ 70 kips
Pass*</td><td rowspan="4">≥ 80 kips
Inconclusive</td></tr>
<tr><td>End</td><td>172 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>274 kips</td></tr>
<tr><td>End</td><td>225 kips</td></tr>
<tr><td>Anchorage</td><td colspan="2">#5 Reinforcing Bars</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

P.3.1 References

1. *Cast-in-Place Concrete Constant Slope Barrier – 54 inch*, Utah Department of Transportation, Salt Lake City, UT, August 2020.

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

3. Bligh, R.P, Briaud, J.L., Abu-Odeh, A., Saez B., D.O., Maddah, L.S., and Kim, K.M., Design Guidelines for Test Level 3 (TL-3) through Test Level 5 (TL-5) Roadside Barrier Systems Placed on Mechanically Stabilized Earth (MSE) Retaining Wall, National Cooperative Highway Research Program (NCHRP) Report 22-20(02), Texas Transportation Institute, College Station, TX, June 2017.

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6. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.

7. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.

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9. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.

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Appendix Q. Virginia Permanent Concrete Barrier MASH Evaluations

Q.1. MASH Equivalency of Virginia DOT F-Shape Concrete Barrier

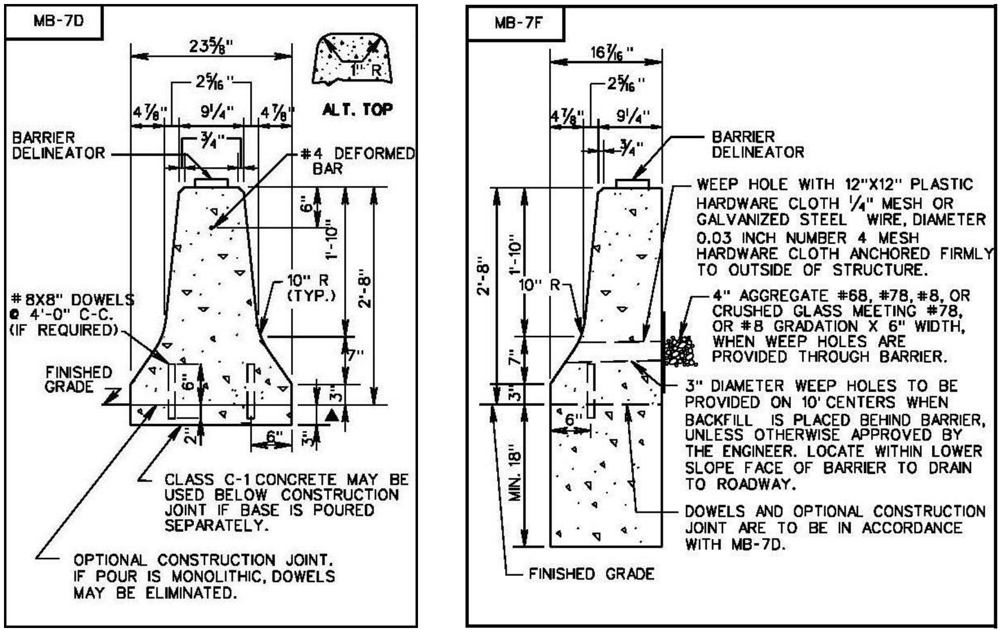

Figure Q.1-1. Virginia DOT F-Shape Barrier Details [1]

<u>Overview and Stability Evaluation</u>

The Virginia DOT Concrete Median barrier is a 32-in. tall, F-shape, minimally reinforced concrete barrier with a 9¼-in. top width. The only reinforcement is a #4 longitudinal bar near the top of the barrier. The barrier can be configured as either a median or half-section, roadside barrier. Design details for the F-shape Concrete Barrier are shown in Figure Q.1-1.

MASH TL-3 standards require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts [2]. MASH test designation no. 3-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 3-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that TL-3 concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle and prevent override [3]. However, F-shape barriers have not been tested at heights below 32 in., and therefore, 32 in. is considered the minimum TL-3 height requirement. Thus, the 32-in. tall Virginia DOT median barrier and half-section barrier has the required height to contain MASH TL-3 impact conditions.

<u>Shape Evaluation</u>

One MASH crash test has been conducted on a barrier with F-shape geometry. In test no. 469467-5-1, a 32-in. F-shape concrete barrier was successfully crash tested to MASH test designation no. 3-11 [4]. To date, MASH test designation no. 3-10 has not been conducted on a permanent F-shape barrier. However, a New Jersey barrier has been successfully crash tested to MASH test designation no. 3-10 [5], and F-shape barriers have been shown to induce less vehicle climb than New Jersey shape barriers due to the reduced toe section height in F-shape geometry. Therefore, it is believed that the F-shape geometry would perform similarly or better than the crashworthy New Jersey barrier. Additionally, vertical concrete barriers, which are known to produce the highest vehicle decelerations of the common concrete barrier shapes, have also been successfully crash tested to MASH test designation no. 3-10 [6]. Since the New Jersey and Vertical barrier geometries have been successfully crash tested to MASH test designation no. 3-10, it is believed that an F-shape barrier would also be crashworthy [7]. Therefore, F-shape geometry has demonstrated the ability to smoothly redirect both 1100C and 2270P vehicles without causing instabilities, excessive vehicle deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Because the Virginia DOT F-Shape Barrier is minimally reinforced, the barrier was outside the scope of the conventional yield line analysis presented in the AASHTO LRFD Bridge Design Specifications [8]. A punching shear analysis could still be conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. Load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table Q.1-1, the design load for a TL-3 barrier is 70 kips distributed over a 4-ft length.

Table Q.1-1. Effective Loads for the Design of MASH Barriers [9]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

The punching shear capacity of the F-Shape Barrier at interior and end sections was 155 kips and 124 kips, respectively. The punching shear capacity of the half-section barrier at interior and end sections was 136 kips and 108 kips, respectively. The calculated punching shear capacities are greater than the required 70 kips, but because yield line strength could not be calculated for the minimally reinforced barrier, analytical methods could not conclusively evaluate the barrier strength for MASH TL-3.

Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the F-shape median barrier and half-section barrier. Currently, no crash tests have been performed on F-shape barriers that are both minimally reinforced and anchored by dowels or footings. Crash testing to MASH TL-3 has been conducted on an unreinforced single-slope barrier anchored by an asphalt keyway [10]. However, the crash tested barrier was significantly taller and wider than the Virginia DOT F-shape barrier, and therefore, could not be used to substantiate the median barrier or half-section barrier crashworthiness. Currently no computational methods exist for the analysis of the footing foundation used to anchor the half-section barrier. Standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [11], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [12], but here again, the minimal reinforcement of the Virginia DOT barrier prevents reliable comparison. Therefore, the strength and anchorage of the median barrier and half-section barrier cannot be justified based on direct comparison.

Overall Evaluation

Based on the evaluation of height, geometry, strength, and anchorage, the Virginia DOT F-shape barrier and F-shape half section barrier may be crashworthy to MASH TL-3, but the minimal reinforcement makes it difficult to qualify barrier strength and anchorage. The evaluation of the barriers at MASH TL-3 was, therefore, inconclusive. The barrier evaluations are summarized in Tables Q.1-2 and Q.1-3.

Table Q.1-2. Virginia F-Shape Concrete Median Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	**TL-4**
Stability		Height = 32 in.		≥ 32 in. Pass	≥ 36 in. Fail
Shape		F-Shape		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	--	≥ 70 kips Inconclusive	
		End	--		
	Punching Shear	Interior	155 kips		
		End	125 kips		
	Anchorage	Dowels		Inconclusive	
		Monolithic Footing		Inconclusive	
Overall MASH Evaluation				Inconclusive	Fail

Table Q.1-3. Virginia F-Shape Concrete Half-Section Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation	
				TL-3	**TL-4**
Stability		Height = 32 in.		≥ 32 in. Pass	≥ 36 in. Fail
Shape		F-Shape		Pass	Not Evaluated due to Failed Stability Criterion
Strength	Yield Line	Interior	--	≥ 70 kips Inconclusive	
		End	--		
	Punching Shear	Interior	136 kips		
		End	108 kips		
	Anchorage	Dowels		Inconclusive	
		Monolithic Footing		Inconclusive	
Overall MASH Evaluation				Inconclusive	Fail

Q.1.1 References

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Appendix R. Wisconsin Permanent Concrete Barrier MASH Evaluations

R.1. MASH Equivalency of the Wisconsin DOT Type S32, S36, S42, and S56 Single-Slope Barriers

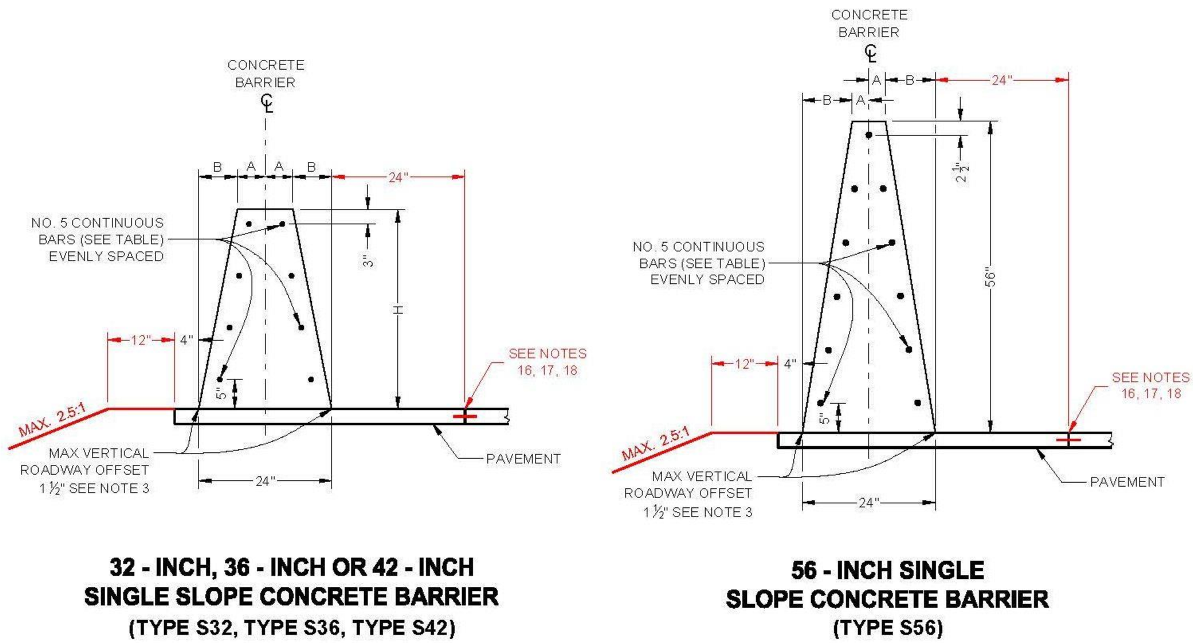


Figure R.1-1. Wisconsin DOT Type S32, S36, S42 and S56 [1]

Table R.1-1. Wisconsin DOT Type S32, S36, S42 and S56 Barrier Dimensions [1]

BARRIER HEIGHT H INCHES	A INCHES	B INCHES	NUMBER OF NO. 5 BARS EACH
32	7	5	8
36	6 ¼	5 ¾	8
42	5 ¼	6 ¾	10
56	3	9	11

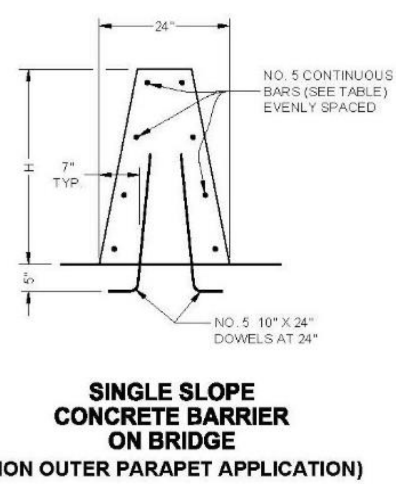


Figure R.1-2. Wisconsin DOT Type S32, S36, S42, and S56 on Bridges [1]

Overview and Stability Evaluation

The Wisconsin DOT Type S32, S36, S42 and S56 barriers are a series of single-slope barriers with a base width of 24 in. and heights of 32 in., 36 in., 42 in., and 56 in., respectively. The barriers are longitudinally reinforced with #5 bars, as detailed in Figure R.1-1 and Table R.1-1. Six vertical #4 stirrups are provided at the barrier end sections in conjunction with a 10-in. deep by 10-ft long monolithic concrete footing reinforced with four #5 bars. The typical anchorage configuration is two #8 dowel bars spaced at 24 in. When installed on a bridge deck, the barrier is anchored with two #5 hooked bars spaced at 24 in., as shown in Figure R.1-2.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees. MASH TL-3 standards, applicable for the Type S32 barrier, require a longitudinal barrier to satisfy safety performance criteria through two different vehicle impacts. MASH test designation nos. 3-10 and 3-11 have the same impact conditions as MASH test designation nos. 4-10 and 4-11, respectively.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations have shown that single-slope concrete barriers with a height of at least 30 in. can contain the 2270P test vehicle [3] and single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle [4–5]. Thus, the Type S36, S42 and S56 barriers have the required height to contain the single-unit truck under MASH TL-4 impact conditions, and the Type S32 barrier has the required height to contain the pickup truck under MASH TL-3 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [6–8], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [9]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [10], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table R.1-2, for TL-3 impacts and for TL-4 impacts on 36-in. tall barriers, the design load is 70 kips distributed over a 4-ft length. This was used to evaluate the Type S32 and Type S36 barriers. The TL-4 design load for barriers with heights greater than 36 in. is 80 kips distributed over a 5-ft length. This was used to evaluate the Type S42 and Type S56 barriers.

The standard barrier configuration does not include vertical reinforcement at interior sections, and therefore, the yield line analysis was limited to barrier end sections. For barriers located on bridges, two #5 hooked bars spaced at 24 in. extend 19 in. into the barrier, and when this extension constituted at least half of the barrier height, a yield line analysis was considered reasonable. For the Type S32 and Type S36 barriers, these dowel bars extended through greater than half the barrier height and a yield line analysis was conducted by conservatively assuming the cantilever moment capacity M_c, at the top of the barrier was equal to zero. The cantilever moment capacity was then determined as the average of the moment capacities at the top and bottom of the barrier. For the taller Type S42 and Type S56 barriers, yield line analysis was not considered reasonable. Punching shear analysis was conducted for interior and end sections of all barriers in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications. The results of the yield line and punching shear analyses are summarized in Table R.1-3.

Table R.1-2. Effective Loads for Design of MASH Barriers [4] and Application in Wisconsin Single-Slope Barrier Evaluation

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft	Applicable Wisconsin Single-Slope Barrier
TL-3	≥30	70	24	4	Type S32
TL-4	36	70	25	4	Type S36
	>36	80	30	5	Type S42 Type S56

Table R.1-3. Computational Analysis Results for Type S32, S36, S42, S56 Barriers

Barrier	Design Load kips	Yield Line Strength, kips		Punching Shear Strength, kips	
		Interior Section	End Section	Interior Section	End Section
S32	70	149*	176	337	259
S36	70	148*	167	331	253
S42	80	--	158	321	256
S56	80	--	152	333	261

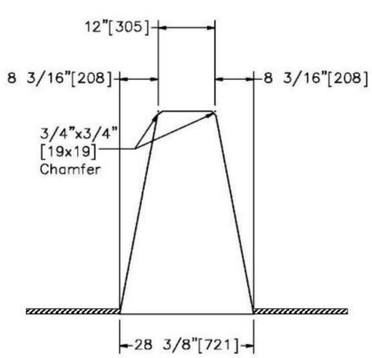
* For bridge deck installation configuration. Capacity is unknown for other barrier configurations.

All calculated strengths were greater than relevant design load for the barrier. For the Type S32 and Type S36 bridge installations, where the full yield line analysis could be completed, the barriers satisfied the MASH loading criteria. However, there was no interior section yield line analysis for non-bridge installations of the S32 and S36 barriers or for either installation type of the S42 and S56 barriers. Accordingly, further evaluation was needed to justify the barriers as crashworthy to MASH criteria.

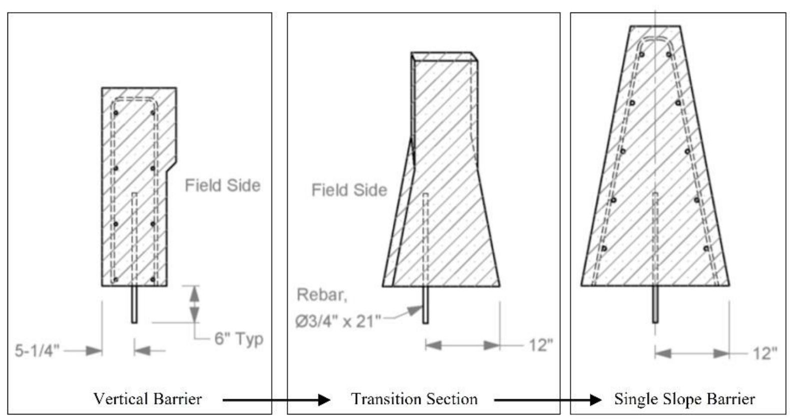
Direct Comparison of Strength and Anchorage

Existing crash test data was reviewed for MASH evaluations that could potentially justify the crashworthiness of the Wisconsin single-slope barrier series. Currently, no crash tests have been performed on barriers with strictly longitudinal reinforcement. However, an unreinforced single-slope barrier with asphalt keyway anchorage [7] and a reinforced concrete barrier with dowel anchorage [11] have been crash tested to MASH TL-3.

In test no. OSSB-1, a 42-in. tall, unreinforced, single-slope concrete barrier with a 1-in. thick asphalt keyway anchorage was crash tested in accordance with MASH test designation no. 3-11. Test no. OSSB-1 resulted in a smooth redirection of the pickup truck, negligible system deflections, and minimal damage to the barrier [7]. Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage is provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [11]. The profiles of the crash tested systems are shown in Figure R.1-3 and a comparison with the 54-in. Median Barrier is provided in.



Test No. OSSB-1



TxDOT T221 Transition

Figure R.1-3. Test No. OSSB-1 Barrier [7] and TxDOT T221 Transition Barrier [11] Profiles

Table R.1-4. Wisconsin DOT Single-Slope Barrier Anchorage Comparison

Evaluation Parameter		OSSB-1 (TL-3)	TxDOT T221 [(a)] 469689-2-2 (TL-3)	Wisconsin DOT Single-Slope Barriers			
				S32	S36	S42	S56
Anchorage	Type	Asphalt Keyway	1 x #6 Dowels	2 x #8 Dowels (Typical) 2 x #5 Dowels (on Bridge)			
	Depth	1 in.	21 in. bar, embed 6 in.	8-in. bar, Embed 4 in. (Typical) 24 in. bar, Embed 5 in. (on Bridge)			
	Spacing	Continuous	8 ft	2 ft			
Geometry	Base Width	28⅜ in.	18 in.	24 in.			
	Top Width	12 in.	10 in.	14 in.	12½ in.	10½ in.	6 in.
	Height	43 in.	37 in.	32 in.	36 in.	42 in.	56 in.
Reinf.	Longitudinal	--	10 x #5	8 x #5	8 x #5	8 x #5	11 x #5
	Vertical	--	2 x #5 @ 12 in.	--	--	--	--
Stability	Section Weight	904 plf	540 plf	633 plf	684 plf	755 plf	1050 plf
	Overturning Stability per ft	1068 ft-lb	405 ft-lb	633 ft-lb	684 ft-lb	755 ft-lb	1050 ft-lb

(a) Height is the average reported for the transition section and section weight was estimated based on average reported dimensions.

The Wisconsin DOT Single-Slope Barriers had similarities with the TL-3 crash tested TxDOT T221 transition dowel-anchored system. The TxDOT T221 transition was anchored by single #6 dowel bars spaced at 8-ft intervals, and each dowel had a 6-in. embedment depth. The typical anchorage configuration of the Single-Slope Barriers uses two #8 bars spaced at 2-ft intervals and embedded 4 in. While this is a smaller embedment depth than the TxDOT T221 transition barrier dowels, the larger bar size and tighter spacing mean that per unit length, the typical configuration provides over 14 times the bar area of the TxDOT T221 transition. The on-bridge configuration uses two #5 hooked bars spaced at 2-ft intervals and embedded 5 in. The embedment depth is 1 in. smaller than the TxDOT T221 transition barrier dowels, but the bars extend 4 in. farther into the barrier. Additionally, the tighter spacing means that per unit length, the on-bridge dowel configuration provides over 5 times the bar area of the TxDOT T221 transition. While the Single-Slope Barriers are more lightly reinforced than the TxDOT T221 transition and the S42 and S56 barriers are taller, the impact on strength and overturning stability is expected to be offset by the larger base widths and higher section weights.

The unreinforced barrier in test no. OSSB-1 provides an additional point of comparison, particularly for the Type S42 and S56 barriers. As part of the research associated with test no. OSSB-1, the 1-in. asphalt keyway anchorage was deemed a critically weak anchorage configuration. The dowel bar anchorage used with the Single-Slope Barriers is anticipated to provide greater strength than the tested 1-in. asphalt keyway. Accordingly, the Type S32, S36, S42, and S56 barriers are considered to have strengths equal to or greater than the MASH TL-3 TxDOT T221 transition and test no. OSSB-1 barriers.

Unfortunately, while the test no. OSSB-1 and TxDOT T221 transition barrier systems provided information on the crashworthiness of unreinforced barriers and dowel-bar anchorages, the systems were only evaluated to MASH TL-3 criteria. There is no known TL-4 crash testing of comparable barriers. Thus, the MASH TL-4 evaluation of the Single-Slope Barriers remains inconclusive until further testing or evaluation is conducted.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Wisconsin Type S32, S36, S42, and S56 barriers are believed to be crashworthy and in compliance with MASH TL-3. Based on a computational evaluation of strength and anchorage, the bridge installation configuration of the Type S36 barrier is believed to be crashworthy and in compliance with MASH TL-4. The Type S42, Type S56 and the non-bridge configuration of the Type S36 may also be crashworthy and in compliance with MASH TL-4, but the absence of vertical reinforcement makes it difficult to qualify the strength and anchorage. The evaluation of these configurations at MASH TL-4 was, therefore, inconclusive. The barrier evaluations are summarized in Tables R.1-5 through R.1-8.

Table R.1-5. Wisconsin Type S32 Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 32 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Fail</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td rowspan="7">Not Evaluated due to Failed Stability Criterion</td></tr>
<tr><td rowspan="6">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>149 kips†</td><td rowspan="4">≥ 70 kips
Pass†</td></tr>
<tr><td>End</td><td>176 kips†</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>337 kips</td></tr>
<tr><td>End</td><td>259 kips</td></tr>
<tr><td rowspan="2">Anchorage</td><td colspan="2">#8 Dowels (Typical Configuration)</td><td>Pass*</td></tr>
<tr><td colspan="2">#5 Bent Bars (Bridge Configuration)</td><td>Pass</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Fail</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

† For bridge deck configuration. Typical configuration yield line strength was unknown and TL-3 barrier strength was justified by direct comparison with available crash tests.

Table R.1-6. Wisconsin Type S36 Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation TL-3	MASH Evaluation TL-4
Stability		Height = 36 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	148 kips†	≥ 70 kips Pass†	≥ 70 kips Pass†
		End	167 kips†		
	Punching Shear	Interior	331 kips		
		End	253 kips		
	Anchorage	#8 Dowels (Typical Configuration)		Pass*	Inconclusive
		#5 Bent Bars (Bridge Configuration)		Pass	Pass
Overall MASH Evaluation				Pass	Pass for Bridge Configuration

* Justified based on available crash tests or finite element simulations.

† For bridge deck configuration. Typical configuration yield line strength was unknown. TL-3 strength was justified by direct comparison with available crash tests and TL-4 strength was inconclusive.

Table R.1-7. Wisconsin Type S42 Barrier Evaluation Summary

Criteria		Barrier Property		MASH Evaluation TL-3	MASH Evaluation TL-4
Stability		Height = 42 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	158 kips		
	Punching Shear	Interior	321 kips		
		End	256 kips		
	Anchorage	#8 Dowels (Typical Configuration)		Pass*	Inconclusive
		#5 Bent Bars (Bridge Configuration)		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

Table R.1-8. Wisconsin Type S56 Barrier Evaluation Summary

Criteria		**Barrier Property**		**MASH Evaluation**	
				TL-3	**TL-4**
Stability		Height = 56 in.		≥ 30 in. Pass	≥ 36 in. Pass
Shape		Single-Slope		Pass	Pass
Strength	Yield Line	Interior	--	≥ 70 kips Pass*	≥ 80 kips Inconclusive
		End	152 kips		
	Punching Shear	Interior	333 kips		
		End	261 kips		
	Anchorage	#8 Dowels (Typical Configuration)		Pass*	Inconclusive
		#5 Bent Bars (Bridge Configuration)		Pass*	Inconclusive
Overall MASH Evaluation				Pass	Inconclusive

* Justified based on available crash tests or finite element simulations.

R.1.1 References

1. SDD 14B32-06a Concrete Barrier Single Slope-Standard, Median Retaining Wall, Anchorages, State of Wisconsin Department of Transportation, November 2018.
2. *Manual for Assessing Safety Hardware (MASH)*, Second Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.
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5. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.
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7. Bielenberg, R.W., Faller, R.K., and Ronspies, K., *MASH TL-3 Evaluation of the Unreinforced, Single-Slope Concrete Median Barrier*, Report No. TRP-03-388-18, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 2018.
8. Williams, W.F., Bligh, R.P., and Menges, W.L., *MASH Test 3-11 of the TxDOT Single-Slope Brige Rail (Type SSTR) on Pan-Formed Bridge Deck*, FHWA/TX-11/91002-3, Texas Transportation Institute, College Station, TX, March 2011.
9. Whitesell, D., Jewell, J., and Meline, R., *Compliance Crash Testing of the Type 60 Median Barrier (TEST 140MASH3C16-04)*, Report No. FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.
10. *LRFD Bridge Design Specifications*, Seventh Edition, Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2017.
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Appendix S. Wyoming Permanent Concrete Barrier MASH Evaluations

S.1. MASH Equivalency of Wyoming DOT Single-Slope Shoulder Barrier

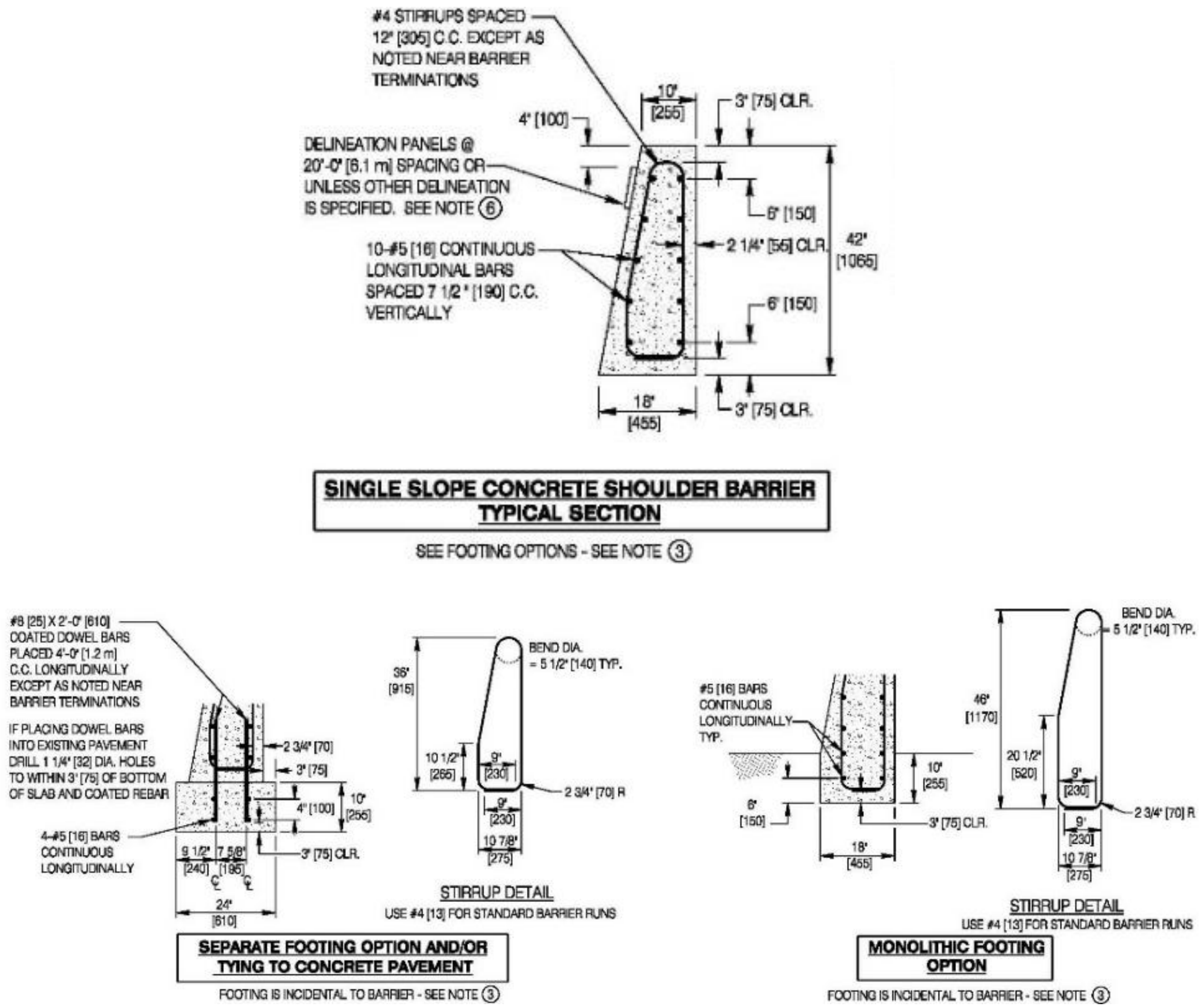

Figure S.1-1. Wyoming DOT Single-Slope Shoulder Barrier [1]

Overview and Stability Evaluation

The Wyoming DOT Single-Slope Shoulder Barrier is a 42-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face. The barrier is vertically reinforced with #4 stirrups at a critical spacing of 12 in. Longitudinal reinforcement consists of five #5 bars along both the front and back sides of the barrier. Anchorage can be provided by embedding #8 dowel bars in a concrete footing or pavement slab, or by extending the vertical reinforcement into a monolithic footing. Design details for the 42-in. Shoulder Barrier are shown in Figure S.1-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no.

4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. tall Single-Slope Shoulder Barrier has the required height to contain the pickup truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table S.1-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. A punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table S.1-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 138 kips for interior sections and 77 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier at interior and end sections was 228 kips and 182 kips, respectively. The end section yield line strength was below the required 80 kips, and therefore, the barrier did not satisfy MASH TL-4 loading criteria. While analytical methods could not conclusively justify adequate barrier strength for MASH TL-4, all calculated capacities were greater than the 70 kips required to satisfy MASH TL-3 loading criteria.

Direct Comparison of Strength and Anchorage

The Wyoming Shoulder Barrier uses a footing foundation. Currently, no computational methods exist for the analysis of this type of anchorage system. However, standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [10], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [11]. The MASH TL-4 simulations included a standalone concrete beam foundation measuring 13 in. wide by 10 in. deep connected to a 36-in. tall single-slope half-section barrier. This beam foundation was deemed to provide adequate performance when the simulated foundation had a 50-ft segment length. Note that the simulations modeled soil conditions representative of those found at the Texas Transportation Institute Proving Ground. Both the 24-in. wide by 10-in. deep separate footing and the 18-in. wide by 10-in. deep monolithic foundation are larger than the footing found adequate for MASH TL-4 in simulations. Therefore, the Wyoming Shoulder Barrier is believed to be in compliance with MASH TL-4 when a segment length of at least 50 ft is provided in strong soil conditions.

Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage was provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [12]. The Wyoming Shoulder Barrier dowel anchorage option specifies two #8 bars spaced 4 ft on-center, which provides anchorage capacity substantially greater than that detailed for the crashworthy TxDOT T221 transition barrier. Therefore, the Wyoming Shoulder Barrier anchorage is adequate for MASH TL-3 with either the monolithic footing or doweled anchorage option. No crash tests have demonstrated adequate MASH TL-4 performance with doweled anchorage, and therefore, the doweled anchorage configuration is inconclusive for MASH TL-4.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Wyoming 42-in. Shoulder Barrier cannot be deemed crashworthy to MASH TL-4 due to end section strength. Additionally, the doweled anchorage option cannot be deemed crashworthy to MASH TL-4. However, the Wyoming 42-in. Shoulder Barrier is believed to be crashworthy and in compliance with MASH TL-3. The barrier evaluation is summarized in Table S.1-2.

Table S.1-2. Wyoming 42-in. Shoulder Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
<tr><th>TL-3</th><th>TL-4</th></tr>
<tr><td colspan="2">Stability</td><td colspan="2">Height = 42 in.</td><td>≥ 30 in.
Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="7">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>138 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 80 kips
Inconclusive</td></tr>
<tr><td>End</td><td>77 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>228 kips</td></tr>
<tr><td>End</td><td>182 kips</td></tr>
<tr><td rowspan="3">Anchorage</td><td colspan="2">Dowel into Footing</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Dowel into Slab</td><td>Pass</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Monolithic Footing</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

S.1.1 References

1. Concrete Barrier Details – Single Slope Shoulder Barrier, Sheet 1 of 2, Wyoming Department of Transportation, April 25, 2018.

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

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4. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Determination of Minimum Height and Lateral Design Load for MASH Test Level 4 Bridge Rails*, FHWA/TX-12/9-1002-5, Texas Transportation Institute, College Station, TX, December 2011.

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10. Sheikh, N.M., Bligh, R.P., Kovar, J.C., Cakalli, S., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of Structurally Independent Foundations for 36-inch Tall Single-Slope Traffic Rail (SSTR) for MASH TL-4*, FHWA/TX-19/0-6968-R7, Texas Transportation Institute, College Station, TX, October 2019.

11. Sheikh, N.M., Bligh, R.P., and Menges, W.L., *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*, Report No. 405160-13-1, Texas Transportation Institute, College Station, TX, August 2009.

12. Sheikh, N.M., Moran, S.M., Cakalli, S., Bligh, R.P., Menges, W.L., Schroeder, G.E., Kuhn, D.L., *Development of MASH TL-3 Transitions for Cast in Place Concrete Barriers*, FHWA/TX-19/0-6968-R8, Texas Transportation Institute, College Station, TX, June 2020.

S.2. MASH Equivalency of the Wyoming DOT Single-Slope Median Barrier

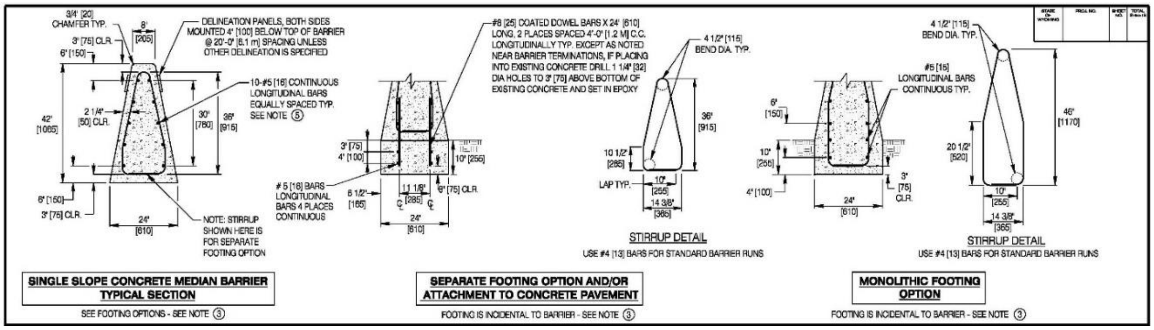

Figure S.2-1. Wyoming DOT Single-Slope Median Barrier [1]

Overview and Stability Evaluation

The Wyoming DOT Single-Slope Median Barrier is a 42-in. tall reinforced concrete barrier with a 10.8-degree single-slope traffic face. The barrier is vertically reinforced with #4 stirrups spaced at 12-in. Longitudinal reinforcement consists of five #5 bars on both the front and back sides of the barrier. Anchorage can be provided by embedding #8 dowel bars in a concrete footing or pavement slab, or by extending the vertical reinforcement into a monolithic footing. Design details for the 42-in. barrier are shown in Figure S.2-1.

MASH TL-4 standards require a longitudinal barrier to satisfy safety performance criteria through three different vehicle impacts [2]. MASH test designation no. 4-10 consists of a 2,420-lb small car (the 1100C vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-11 consists of a 5,000-lb pickup truck (the 2270P vehicle) impacting the system at a speed of 62 mph and an angle of 25 degrees. MASH test designation no. 4-12 consists of a 22,046-lb single-unit truck (the 10000S vehicle) impacting the system at a speed of 56 mph and an angle of 15 degrees.

For a rigid concrete barrier to be deemed crashworthy without testing, it must have sufficient height to prevent vehicle override, a front-face geometry which safely redirects passenger vehicles without causing instabilities or rollovers, and the strength to contain and redirect vehicles. Previous FE simulations and crash tests have shown that single-slope concrete barriers with a height of at least 36 in. can contain the 10000S test vehicle and prevent override [3–4]. Thus, the 42-in. Single-Slope Median Barrier has the required height to contain the single-unit truck under MASH TL-4 impact conditions.

Shape Evaluation

Single-slope concrete barrier geometry has been proven crashworthy in multiple MASH tests with passenger vehicles. MASH test designation no. 3-11 has been conducted on single-slope barriers ranging in height from 32 in. to 42 in. [5–7], and MASH test designation no. 3-10 was conducted on a 36-in. tall single-slope barrier [8]. The traffic faces were sloped at 9 or 11 degrees, the two most common angles for single-slope concrete barriers. In all tests, the 1100C and 2270P vehicles were smoothly redirected with limited roll and pitch angular displacements. Therefore, the geometry of single-slope concrete barriers has demonstrated the ability to safely redirect passenger vehicles without causing instabilities, excessive deformations, or excessive vehicle decelerations.

Strength and Anchorage Evaluation

Computational Analysis of Strength and Anchorage

Yield line analysis was used to evaluate the strength and anchorage capacity of the barrier. The analysis method was similar to that presented in the AASHTO LRFD Bridge Design Specifications [9], but the load requirements were updated to reflect the MASH impact loads determined as part of NCHRP Project 22-20(2). As seen in Table S.2-1, the design load for a TL-4 barrier with a height greater than 36 in. is 80 kips distributed over a 5-ft length. Thus, 5 ft was utilized as the L_t term in the yield line equations. A punching shear analysis was conducted in accordance with Section 5 of the AASHTO LRFD Bridge Design Specifications.

Table S.2-1. Effective Loads for Design of MASH Barriers [3]

Test Level	Barrier Height H, in.	Impact Force F_t, kips	Effective Height H_e, in.	Effective Length L_t, ft
TL-3	≥30	70	24	4
TL-4	36	70	25	4
	>36	80	30	5

Yield line analysis determined barrier strength to be 187 kips for interior sections and 89 kips for end sections adjacent to discontinuities (expansion gaps and joints). The punching shear capacity of the barrier was 237 kips for interior sections and 194 kips for end sections. All calculated capacities were greater than the required 80 kips. While the computational analyses were favorable, the adequacy of the anchorage details must also be evaluated. As discussed below, existing crash test data was reviewed to evaluate the MASH TL-4 performance of the dowel anchorage and footing anchorage.

Direct Comparison of Strength and Anchorage

The Wyoming Single-Slope Median Barrier uses a footing foundation. Currently, no computational methods exist for the analysis of this type of anchorage system. However, standalone concrete beam foundations have been evaluated with FE simulations to MASH TL-4 [10], and a MASH TL-3 crash test was conducted on a barrier with a standalone foundation [11]. The MASH TL-4 simulations included a standalone concrete beam foundation measuring 13 in. wide by 10 in. deep that was connected to a 36-in. tall single-slope half-section barrier. The beam foundation was deemed to provide adequate performance when the simulated foundation had a 50-ft segment length. Note that the simulations modeled soil conditions representative of those found at the Texas Transportation Institute Proving Ground. Both the separate and monolithic footing options for the Wyoming Single-Slope Median Barrier are 24 in. wide by 10 in. deep, which is larger than the footing found adequate for MASH TL-4 in simulations. Therefore, the Wyoming Single-Slope Median Barrier footing anchorages are believed to be adequate for MASH TL-4 impacts when a segment length of at least 50 ft is provided in strong soil conditions.

Crash testing has also been performed on a barrier system anchored with dowel bars. The TxDOT T221 transition barrier was a transition segment designed for use between a 42-in. tall, single-slope concrete barrier and a 32-in. tall vertical concrete barrier. Anchorage was provided by #6 bars spaced longitudinally at 8 ft and epoxied 6 in. into the concrete pavement. In test no. 469689-2-2, the transition section redirected the pickup truck and satisfied the safety performance criteria of MASH test designation no. 3-21 [12]. The Wyoming Single-Slope Median Barrier dowel anchorage option specifies two #8 bars spaced 4 ft on-center, which provides substantially more capacity than the crashworthy T221 transition barrier anchorage. Therefore, the Wyoming Single-Slope Median Barrier anchorage is deemed adequate for MASH TL-3 with either the monolithic footing or doweled anchorage option. No crash tests have demonstrated adequate MASH TL-4 performance with doweled anchorage, and therefore, the TL-4 crashworthiness of the doweled anchorage option remains inconclusive.

Overall Evaluation

Based on this evaluation of height, geometry, strength, and anchorage, the Wyoming 42-in. Median Barrier is believed to be crashworthy and in compliance with MASH TL-4 with the monolithic footing anchorage option, and crashworthy to MASH TL-3 for the doweled anchorage options. The barrier evaluation is summarized in Table S.2-2.

Table S.2-2. Wyoming 42-in. Median Barrier Evaluation Summary

<table>
<tr><th colspan="2" rowspan="2">Criteria</th><th colspan="2" rowspan="2">Barrier Property</th><th colspan="2">MASH Evaluation</th></tr>
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Pass</td><td>≥ 36 in.
Pass</td></tr>
<tr><td colspan="2">Shape</td><td colspan="2">Single-Slope</td><td>Pass</td><td>Pass</td></tr>
<tr><td rowspan="7">Strength</td><td rowspan="2">Yield Line</td><td>Interior</td><td>187 kips</td><td rowspan="4">≥ 70 kips
Pass</td><td rowspan="4">≥ 80 kips
Pass</td></tr>
<tr><td>End</td><td>89 kips</td></tr>
<tr><td rowspan="2">Punching Shear</td><td>Interior</td><td>237 kips</td></tr>
<tr><td>End</td><td>194 kips</td></tr>
<tr><td rowspan="3">Anchorage</td><td colspan="2">Dowel into Footing</td><td>Pass*</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Dowel into Slab</td><td>Pass</td><td>Inconclusive</td></tr>
<tr><td colspan="2">Monolithic Footing</td><td>Pass*</td><td>Pass*</td></tr>
<tr><td colspan="4">Overall MASH Evaluation</td><td>Pass</td><td>Inconclusive</td></tr>
</table>

* Justified based on available crash tests or finite element simulations.

S.2.1 References

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