DEPARTMENT OF TRANSPORTATION

Review and Assessment of Past MnDOT Bridge Barrier Types

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16. Abstract (Limit: 250 words)

Many Minnesota bridges have older barriers or parapets that met the design code at the time of construction in the 1950s. Many of these bridge barriers no longer meet current strength and performance requirements of *NCHRP Report 350* or the *Manual for Assessing Safety Hardware* (MASH). As the Minnesota Department of Transportation (MnDOT) begins to rehabilitate older existing bridges, a determination needs to be made as to whether the existing older type of barrier can remain in place or if it should be rehabilitated or replaced with a newer style barrier.

This research documented the number of bridges in Minnesota that have One-Line Rails and type G, J, and F barriers and when they were built. Evaluations were then performed for both the structural strength and crashworthiness of each type of barrier and recommended guidance and evaluation criteria were developed to determine when an existing barrier should be upgraded or replaced.

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REVIEW AND ASSESSMENT OF PAST MNDOT BRIDGE BARRIER TYPES

FINAL REPORT

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LIST OF ABBREVIATIONS

AASHTO – American Association of State Highway and Transportation Officials

LRFD – Load and Resistance Factor Design

MnDOT - Minnesota Department of Transportation

MASH – Manual for Accessing Safety Hardware

TL – Test Level

TTI –Texas A&M Transportation Institute

EXECUTIVE SUMMARY

For Task 1 of this project, a site visit was conducted to gather and assess bridge barrier details and information. The site visit occurred over four working days to gather and attain information on the selected bridge barriers. The site visit was used to assess the condition of the bridge barriers. Also, the site visit allowed Texas A&M Transportation Institute (TTI) to review and collect details and information that would be used for other tasks in the project. TTI researchers used information gathered during the field site visit to analyze and evaluate strength and performance (i.e., structural adequacy and occupant risk evaluation criteria) of the bridge barrier systems to determine if they were Manual for Accessing Safety Hardware (MASH) compliant. The bridge barriers were categorized based on their condition as poor, fair or good. Poor condition bridge barriers had severe delamination or cracking with exposed reinforced steel. Fair condition bridge barriers had mild delamination or cracking. Good condition bridge barriers had little to no delamination or cracking. The information gathered from this task was used for further work on this project.

For Task 2 of this project, the information collected in Task 1 along with the information received from MnDOT were used to evaluate several widely used barrier types currently in the MnDOT inventory. The barriers analyzed for this task consist of Minnesota types G, J, and F, and the One Line Bridge Barrier System, which consists of a concrete post and single rail element usually installed on a concrete curb that varies in thickness and width. A total of 1,721,892 lineal feet of barrier exists on MnDOT bridges. Many of these barriers were constructed in the late 1960s and early 70s. These four barrier types have the greatest use, historically, in the MnDOT inventory (see Figure 2-1). The purpose of this task was to access the current four typical barrier types used in the MnDOT inventory with respect to MASH (ref. 1) strength and performance criteria. A summary of the findings and retrofit recommendations for the different barrier types G, J, and F and the One Line Bridge Barrier System are provided as follows.

As part of Task 2 of this project, an analysis procedure with respect to the current MASH strength and performance criteria for MASH TL-3 is applied to all of the bridge barriers investigated for this project. To evaluate the critical barriers according to MASH performance specifications, three different criteria are considered. These criteria consist of stability, barrier geometrics, and strength. The analysis methodologies used to evaluate these criteria are briefly presented below. The results of the analyses are used to determine which barriers can be considered MASH compliant and which will require further analysis or crash testing to establish MASH compliance.

Stability Requirements for MASH Bridge Barriers

For a bridge barrier to be considered a MASH acceptable barrier, a minimum height must be met to ensure stability of the vehicle. This minimum height for a MASH TL-3 compliant bridge barrier was established previously to be 29 inches. This criterion was used to evaluate all the barrier types in this project with respect to MASH TL-3 acceptance. For this project, if the minimum barrier height was satisfied, the barrier was considered to satisfactorily meet stability requirements.

Geometric Requirements for MASH Bridge Barriers

The geometric relationships for bridge barriers contained in Section 13 of the current *AASHTO LRFD Bridge Design Specifications* (Figure 2-2) were applied to evaluate barrier geometry. These relationships pertain to the potential for wheel, bumper or hood snagging on elements of the bridge barrier. Severe snagging can lead to a number of undesirable consequences including increased occupant compartment deformation, higher accelerations and occupant risk indices, and vehicle instability. Both AASHTO figures are used to analyze barrier geometry for all MASH test levels. These figures were used to establish the acceptable performance criteria for the bridge rails evaluated in this project.

NCHRP Project 22-35 is currently evaluating both AASHTO Section 13 geometric figures. Under NCHRP Project 22-35, TTI researchers will either validate or update these figures with respect to MASH specifications. Until the results of this research study are available, these AASHTO geometric relationships are still valid.

For a barrier to be given a Satisfactory (S) designation for the geometric evaluation criteria, the barriers' geometric data points (i.e., post setback distance, rail contact width to height ratio, and vertical clear opening) must plot in the AASHTO Figure A13.1.1-2 and A13.1.1-3 acceptable regions. The Preferred region in AASHTO Figure A13.1.1-2 and the Low Snag Potential region in AASHTO Figure A13.1.1-3 are considered the acceptable regions. A barrier is given a Marginal (M) designation for the geometric evaluation criteria if the barrier's geometric data points plot between the Preferred and Not Recommended regions (Figure A13.1.1-2) or the Low Snag Potential and High Snag Potential regions (Figure A13.1.1-3). A barrier is given a Not Satisfactory (NS) designation for the geometric evaluation criteria if the barrier's geometric data points plot in the Not Recommended region (Figure A13.1.1-2) or the High Snag Potential region (Figure A13.1.1-3).

Strength Requirements for MASH Bridge Barriers

Section 13 of the *AASHTO LRFD Bridge Design Specifications* contains procedures for analyzing the structural capacity of different types of bridge barriers (e.g., steel, concrete). These procedures were used to evaluate the strength of the selected barriers for this project. Using these procedures, an analysis of the strength of the selected barriers was performed using updated loads for MASH Test Level 3 impact conditions. These updated loads were used and published as part of NCHRP Project 20-07/Task 395. All barriers analyzed for this project were evaluated with respect to current recommended MASH TL-3 impact loading conditions. For a G barrier, the strength of the metal rails, posts, and post connections were analyzed to obtain the overall strength of the barrier system. For MASH Test Level 3, a barrier was considered MASH compliant if the barrier met the minimum transverse impact load requirements. The transverse impact design load (F_t) requirement is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface for MASH TL-3. All barriers, including end posts (separate and integral), and any retrofits that were developed for this project, were evaluated with respect to this loading requirement. These loads and application heights were used and published as part of NCHRP Project 20-07/Task 395.

At the start of this project, TTI researchers received drawings and details for the typical J or F barriers, One-Line railings, and G barriers from MnDOT. TTI researchers grouped the J and F barrier types into a single category for analysis purposes. The One-Line railings were grouped into separate categories. TTI was unable to group the G barriers due to the unique features of each G barrier received from MnDOT. Therefore, all G barriers were analyzed separately under this task. Within each group type (J/F, and One-Line), TTI researchers sub-grouped the barriers within each group based on the common geometric features and steel reinforcement configurations. Within each subgroup of common barriers, TTI selected the most critical barrier design for detailed analyses and assessment with respect to MASH specifications. Please refer to Table 2.1 through Table 2.3 to see how the different barrier types were grouped. These tables also provide the results of the analyses and evaluations with respect to MASH strength and performance criteria. For all the different barrier types, retrofit design information to achieve MASH TL-3 strength and performance requirements was developed and provided as part of Task 3 of this project. A summary of the finding and results for each barrier type is provided as follows

MnDOT One-Line Railings

The One-Line bridge rail type constitutes approximately 13% of the barriers used on MnDOT bridges. Approximately 226,000 lineal feet of this barrier type is currently in service. The earliest construction of these barrier types dates to 1949. The latest (newest) construction of these barrier types occurred in August 1970, according to MnDOT records. The overall condition of the One-Line railings on state owned bridges was assessed to be 75.4% good, 18.4% fair, and 6.2% poor to severe. TTI received drawings and details of the One-Line railing types used on MnDOT bridges. Many of the designs use a small two-tube pedestrian rail mounted to the top of the concrete beam elements. The strength of these pedestrian rail elements was not considered in our strength and performance analyses for this project. For additional information, please refer to the analyses and details on the One-Line railings included in this report.

Fourteen One-Line barriers were evaluated for this project. These barriers were categorized by geometry in Table 2.2 of this report. All these barriers were analyzed with respect to the strength and performance criteria for MASH TL-3 discussed previously, and all were found NS based on geometric and strength criteria.

Recommended strategies for retrofitting are provided for the One-Line barrier type. These retrofits include slip forming an F-shaped barrier type on the One-Line designs. Also, guidance is provided on designing a cast-in-place vertical wall with vertical dowels into the deck and curb. As stated previously, the minimum height for these new retrofits is 29 inches for MASH TL-3. Design guidance was also developed based on the exposed height and width of the curbs for the One-Line retrofit barriers (see Table 3.1). Please refer to Sections 2.3 and 3.3 of this report for additional information.

MnDOT G Barriers

The MnDOT Type G bridge barrier constitutes approximately 10% of the barriers used on MNDOT Bridges. Approximately 177,000 lineal feet of this barrier type is currently in service on MnDOT bridges. The earliest construction of these barrier types dates to February 1970, according to MnDOT records. The latest (newest) construction of these barrier types occurred in January 1977. The overall condition of the G barriers on state-owned bridges was assessed to be 79.5% good, 18.7% fair, and 2.0% poor to severe. TTI received drawings and details of the G barrier types used on MnDOT bridges. Many of the designs used a tubular steel rail element with a large angle section that anchors to the top of the concrete parapet. The strength of these tubular rail elements will be considered if they are 4 inches in diameter or greater with heavy thick wall sections. For additional information, please refer to the analyses and details on the G barriers included in this report.

Three G barrier types were analyzed and evaluated as part of this project. These barriers were generally unsatisfactory in regard to meeting MASH TL-3 performance criteria. For all of the G barrier cases, removal of the single steel tube is recommended. Increasing the height of the barrier can be achieved by casting a new concrete extension on top of the barrier or anchoring a steel tube. Design information was provided for the G barrier retrofits to achieve acceptable MASH TL-3 performance criteria. Please refer to Section 4.4 of this report for additional information on the G barrier retrofits.

MnDOT J and F Barriers

Type J or F barriers constitute the largest percentage of barriers on MnDOT bridges. Approximately 55% (946,000 lineal feet) are currently in service. The earliest construction of these barrier types dates to December 1976 (type J), according to MnDOT records. The overall condition of the J barriers on state owned bridges was assessed to be 72.1% good, 26.7% fair, and 1.3% poor to severe. TTI has received drawings and details of the J barriers. Many of the designs used since the mid 1970s use separate end posts at the ends of the barriers. The strength of these separate end posts was considered in our analyses for both barrier types. For additional information, please refer to the analyses and details on the J barrier included in this memorandum.

Twenty-five J and F shaped barriers were analyzed as part of this project. These barriers were generally unacceptable due to the separate end posts located on the ends of the barriers. A new separate end post was designed and developed for this project. This new end post can be used for the J, F and G barrier types. The new end post is supported by a new shape transition end anchored to a small grade beam that is anchored to a 24-inch diameter drilled shaft. Details were developed for the drilled shaft and grade beam for this project. MASH-approved shape transition sections were also developed for the J, F, and G barrier types, which can be used in conjunction with the new grade beam and drilled shaft design or for end posts on approach panels. J and F barriers with an integral end post were generally found to meet MASH TL-3 criteria. (Please refer to Section 3.1 of this report for additional information.) In cases where retrofitting new J and F barrier sections was required, design guidance has been provided as part of this project. Please refer to Section 3.5 of this report for additional information.

CHAPTER 1: FIELD REVIEW AND INFORMATION ON MNDOT BRIDGE BARRIERS

1.1 OVERVIEW

A short site visit was conducted to gather and assess bridge barrier details and information. The site visit took four working days to gather and attain information on the selected bridge barriers. The site visit was used to assess the condition of the bridge barriers. Also, the site visits allowed Texas A&M Transportation Institute (TTI) to review and collect details and information that were used for tasks 2 and 3. From the information and details that were gathered on the field site visits, TTI researchers analyzed and evaluated strength and performance (i.e., structural adequacy and occupant risk evaluation criteria) of the bridge barrier systems to determine if they were MASH compliant. The bridge barriers were categorized as poor, fair or good based on their condition. Poor condition bridge barriers had severe delamination or cracking with exposed reinforced steel. Fair condition bridge barriers had mild delamination or cracking. Good condition bridge barriers had little to no delamination or cracking. A description of the bridge barriers along with field site visit photos and details of the bridge barriers are presented below. This information will be used for further work on this project.

1.2 J BARRIER - SITE VISIT SUMMARY

1.2.1 Bridge No. 27169

The MnDOT J barrier on Bridge No. 27169 is a reconstructed One Line bridge barrier and is in fair condition. The bridge barrier has a total height of 32 inches (from the top of a 2-inch approximate overlay), a bottom width of 25 inches, and a top width of 16 inches. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 4 Grade 60 rebar is used for transverse reinforcement. Figure A1-1 in Appendix A1 shows the site visit photos of the bridge barrier. Figure A1-2 in Appendix A1 shows the details of the bridge barrier.

1.2.2 Bridge No. 19056

The MnDOT J barrier on Bridge No. 19056 is in poor condition. The bridge barrier has multiple areas of delamination and cracking. The bridge barrier has a total height of 32 inches (from the top of a 2-inch approximate overlay), a bottom width of 18 inches, and a top width of 9 inches. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 5 Grade 60 rebar is used for transverse reinforcement. Figure A1-3 in Appendix A1 shows the site visit photos of the bridge barrier. Figure A1-4 in Appendix A1 shows the details of the bridge barrier.

1.2.3 Bridge No. 82502

The MnDOT J barrier on Bridge No. 82502 is a reconstructed new single slope bridge barrier. The bridge barrier is in good condition. The original J barrier had a total height of 33 inches, a bottom width of 21 inches, and a top width of 9 inches. Number 4 Grade 60 rebar was used for longitudinal reinforcement and Number 5 Grade 60 rebar was used for transverse reinforcement for the original J barrier. Figure A1-5 in Appendix A1 shows the site visit photos of the new single slope bridge barrier. Figure A1-6 in Appendix A1 shows the details of the original J barrier

1.2.4 Bridge No. 19042

The MnDOT J barrier on Bridge No. 19042 is in good condition. The bridge barrier has a total height of 32 inches (from the top of a 2-inch approximate overlay), a bottom width of 18 inches and a top width of 9 inches. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 5 Grade 60 rebar is used for transverse reinforcement. Figure A1-7 in Appendix A shows the site visit photos of the bridge barrier. Figure A1-8 in Appendix A1 shows the details of the bridge barrier.

1.2.5 Bridge No. 62828

The MnDOT J barrier on Bridge No. 62828 is in good condition. There is a chain link fence located along the top of the bridge barrier. The bridge barrier has a total height of 32 inches (from the top of a 2-inch approximate overlay), a bottom width of 21 inches, and a top width of 12 inches. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 5 Grade 60 rebar is used for transverse reinforcement. Figure A1-9 in Appendix A1 the field site visit photos of the bridge barrier. Figure A1-10 in Appendix A1 shows the details of the bridge barrier.

1.3 ONE LINE BRIDGE RAIL - SITE VISIT SUMMARY

1.3.1 Bridge No. 27944

The MnDOT One Line Bridge Rail on Bridge No. 27944 is retrofitted with an infill facing the roadway. The bridge parapet is in good condition. The bridge parapet has a total height of 32-1/4 inches (from the top of a 2-inch approximate overlay) and a post width of 11 inches. The total height includes a 6-inch high curb. Number 7 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 4 Grade 60 rebar is used for transverse reinforcement in the curb. Figure A2-1 in Appendix A2 shows the site visit photos of the bridge parapet. Figure A2-2 in Appendix A2 shows the details of the bridge parapet.

1.3.2 Bridge No. 30505

The MnDOT One Line Bridge Rail on Bridge No. 30505 is an older bridge parapet that is in poor condition. The bridge parapet has various areas of delamination and exposed rebar due to severe cracking. The bridge parapet has a total height of 34-1/4 inches (including a 6-inch high curb) and a 9-inch wide by 14-inch deep concrete beam. Number 7 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-3 in Appendix A2 shows the site visit photos of the bridge parapet. Figure A2-4 in Appendix A2 shows the details of the bridge parapet.

1.3.3 Bridge No. 69834

The MnDOT One Line Bridge Rail on Bridge No. 69834 is in good condition. This bridge rail is a combination metal rail on top of a concrete post-and-beam rail. The total height is 39 inches on top of a 10-inch high by 48-inch wide walkway. The concrete post-and-beam rail has a total height of 28 inches and a 9-inch wide by 14-inch deep concrete beam. The bridge rail has a 4-inch diameter extra strong pipe top rail element. Number 8 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-5 in Appendix A2 shows the site visit photos of the bridge rail. Figure A2-6 in Appendix A2 shows the details of the bridge rail

1.3.4 Bridge No. 70802

The MnDOT One Line Bridge Rail on Bridge No. 70802 is in good condition. The bridge rail has a total height of 38-1/4 inches (including a 10-inch high curb) and an 8-inch wide by 14-inch deep concrete beam. Number 8 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-7 in Appendix A2 shows the site visit photos of the bridge rail. Figure A2-8 in Appendix A2 shows the details of the bridge rail.

1.3.5 Bridge No. 25505

The MnDOT One Line Bridge Rail on Bridge No. 25505 is in good condition. The bridge rail has a total height of 34-1/4 inches (including a 6-inch high curb) and a 9-inch wide by 14-inch deep concrete beam. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-9 in Appendix A2 shows the site visit photos of the bridge rail. Figure A2-10 in Appendix A2 shows the details of the bridge rail.

1.3.6 Bridge No. 82804

The MnDOT One Line Bridge Rail on Bridge No. 82804 is in poor condition. The bridge rail has severe deterioration on the south end of the bridge. The bridge rail has a total height of 38-1/4 inches (including a 10-inch high curb) and a 9-inch wide by 14-inch deep concrete beam. Number 7 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-11 in Appendix A2 shows the site visit photos of the bridge rail. Figure A2-12 in Appendix A2 shows the details of the bridge rail.

1.3.7 Bridge No. 9805

The MnDOT One Line Bridge Rail on Bridge No. 9805 is in poor condition. The bridge rail has exposed rebar in the concrete post and also in the concrete beam elements. This bridge rail is a combination metal rail on top of a concrete post-and-beam rail. The total height is 30 inches to the centerline of the top rail element. The concrete post-and-beam rail has a total height of 18 inches and a 13-inch wide by 12-inch deep concrete beam. The bridge rail has a 4-inch diameter extra strong pipe top rail element. Number 6 Grade 60 rebar is used for the vertical reinforcement in the post. Due to dangerous road conditions, no site visit photos were taken of the bridge rail. Figure A2-13 in Appendix A2 shows the details of the bridge rail.

1.3.8 Bridge No. 62069

The MnDOT One Line Bridge Rail on Bridge No. 62069 is in fair condition. This bridge rail is a combination metal handrail on top of a concrete post-and-beam rail. For sections that include a walkway, the total rail height is 42 inches to the centerline of the top handrail element on top of a 10-inch high by 72-inch wide walkway. For sections that do not include a walkway, the total rail height is 48-1/4 inches to the centerline of the top handrail element (including a 6-inch high curb). The concrete post-and-beam rail has a total height of 28 inches (above the walkway or curb) and a 9-inch wide by 14-inch deep concrete beam. The handrail elements are 2-inch std. pipes. Number 7 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-14 in Appendix A2 shows the site visit photos of the bridge rail. Figure A2-15 in Appendix A2 shows the details of the bridge rail.

1.3.9 Bridge No. 27042

The MnDOT One Line Bridge Rail on Bridge No. 27042 is in poor condition. The bridge rail has various locations of corrosion of the steel reinforcement in the concrete post elements. The bridge rail has a total height of 34-1/4 inches (including a 6-inch high curb) and a 9-inch wide by 14-inch deep concrete beam. Number 7 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Figure A2-16 in Appendix A2 shows the site visit photos of the bridge rail. Figure A2-17 in Appendix A2 shows the details of the bridge rail.

1.3.10 Bridge No. 62040

The MnDOT One Line Bridge Rail on Bridge No. 62040 is a reconstructed J barrier. The bridge rail is in good condition. The details received from MnDOT are of the original One Line Bridge Rail. The bridge rail has a total height of 34-1/4 inches (including a 6-inch high curb) and a 9-inch wide by 14-inch deep concrete beam. Number 7 Grade 60 rebar is used for the vertical reinforcement on the traffic side of the post and Number 6 Grade 60 rebar is used for the vertical reinforcement on the field side of the post. Number 6 Grade 60 rebar is used for longitudinal reinforcement, Number 3 Grade 60 rebar is used for transverse reinforcement in the post, and Number 2 Grade 60 rebar is used for transverse reinforcement in the beam. Due to dangerous road conditions, no site visit photos were taken of the bridge rail. Figure A2-18 in Appendix A2 shows the details of the original One Line Bridge Rail.

1.4 G BARRIER - SITE VISIT SUMMARY

1.4.1 Bridge No. 09830

The MnDOT G Barrier on Bridge No. 09830 is in good condition. This bridge barrier is a combination metal rail on top of a concrete barrier. The total height is 40-5/8 inches. The concrete barrier has a height of 28 inches, a bottom width of 21 inches, and a top width of 12 inches. The bridge barrier has a 4-inch diameter extra strong pipe top rail element. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 5 Grade 60 rebar is used for transverse reinforcement. Figure A3-1 in Appendix A3 shows the site visit photos of the bridge barrier. Figure A3-2 in Appendix A3 shows the details of the bridge barrier.

1.4.2 Bridge No. 19021

The MnDOT G barrier on Bridge No. 19021 is in good condition. This bridge barrier is a combination metal rail on top of a concrete barrier. The total height is 40-5/8 inches. The concrete barrier has a height of 28 inches, a bottom width of 21 inches, and a top width of 12 inches. The bridge barrier has a 4-inch diameter extra strong pipe top rail element. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 5 Grade 60 rebar is used for transverse reinforcement. Figure A3-3 in Appendix A3 shows the site visit photos of the bridge barrier. Figure A3-4 in Appendix A3 shows the details of the bridge barrier.

1.4.3 Bridge No. 86812

The MnDOT G barrier on Bridge No. 86812 is in poor condition. The bridge barrier has severe spalling. Also, longitudinal cracks along the bridge barrier cause some exposure to steel reinforcement. This bridge barrier is a combination metal rail on top of a concrete barrier. The total height is 40-5/8 inches. The concrete barrier has a height of 28 inches, a bottom width of 21 inches, and a top width of 12 inches. The bridge barrier has a 4-inch diameter extra strong pipe top rail element. Number 4 Grade 60 rebar is used for longitudinal reinforcement and Number 5 Grade 60 rebar is used for transverse reinforcement. Figure A3-5 in Appendix A3 shows the site visit photos of the bridge barrier. Figure A3-6 in Appendix A3 shows the details of the bridge barrier.

CHAPTER 2: BARRIER DETAILING, ANALYSES, AND DESIGN AND IMPLEMENTATION STEPS

2.1 OVERVIEW

TTI has received a detailed list of Minnesota Department of Transportation (MnDOT) owned barrier types throughout the state. This list comprises numerous barrier types. Namely Type J and F, One line and Type G barriers. A total of 1,721,892 lineal feet of barrier exists. TTI has performed a field review of some these barriers. This field review was performed on September 17-20, 2018. Based on this review, TTI understands the condition of the typical barriers currently in use. Also, TTI has been provided detailed engineering drawings of several barriers that were reviewed in the field study.

2.1.1 Task 2: Barrier Detailing, Analyses and Design

For Task 2, the information collected in Task 1 along with the information received from MnDOT was used to evaluate several widely used barrier types currently in the MnDOT inventory. The barriers analyzed for this task consist of the Minnesota Types G, J, F, and One Line Bridge Rail. The One Line Bridge Rail System consists of a concrete post and single rail usually installed on a concrete curb that varies in thickness and width. As previously mentioned, a total of 1,721,892 lineal feet of barrier exists on MnDOT bridges. Many of these barriers were constructed in the late 1960’s and early 70’s. These four barrier types have the greatest use, historically, in the MnDOT inventory. The purpose of this task is to assess these four typical barrier types with respect to MASH (ref. 1) strength and performance criteria. A breakdown of the barrier types is shown in Figure 2-1 as follows.

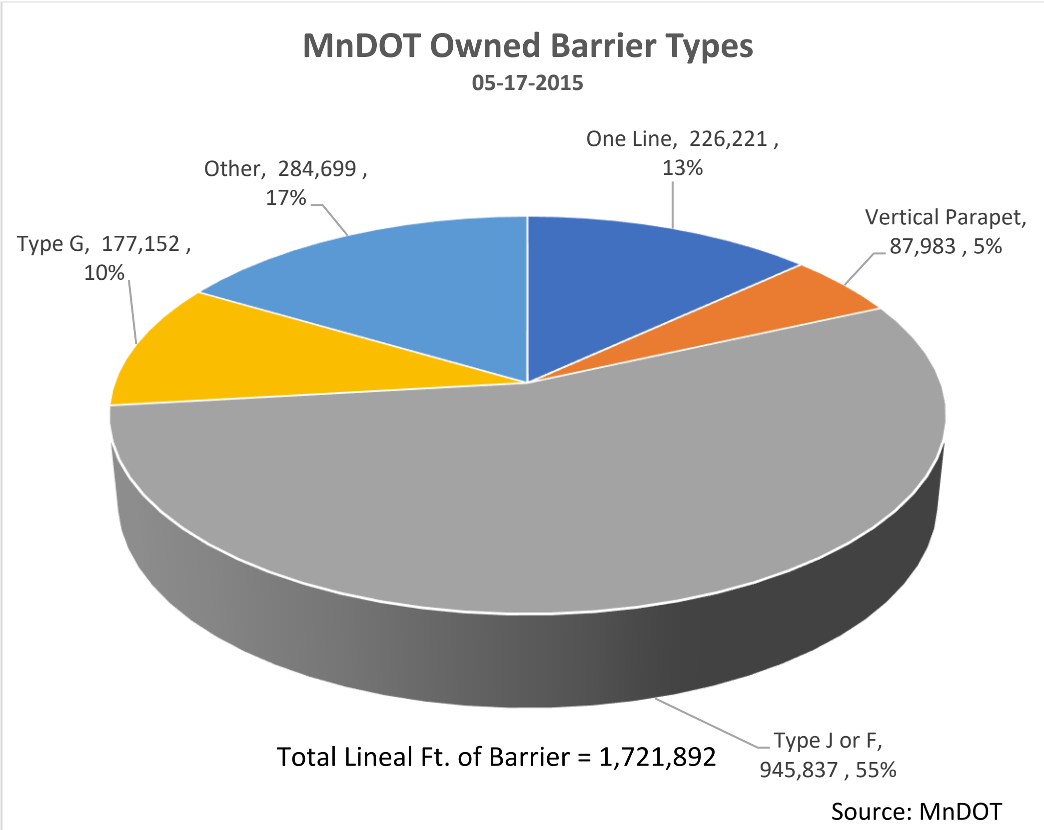


Figure 2-1 Percentage of Barrier Types on MnDOT Bridges, Types G, One-Line, J or F.

A brief summary of the four different barrier types analyzed for this task are presented below.

1.1.1.1 MnDOT One-Line Railings

The One-Line bridge rail type constitutes approximately 13% of the barriers used on MnDOT Bridges. Approximately 226,221 lineal feet of this barrier type is currently in service. The date of the earliest construction of these barrier types date back to 1949. The latest (newest) construction of these barrier types date back to August 1970. According to MnDOT inspection records, the overall condition of the One-Line railings on state owned bridges were assessed to be 75.4% Good, 18.4% fair and 6.2% poor to severe. TTI has received drawings and details of the One-Line railing types used on MnDOT bridges. Many of the designs use a small 2-tube pedestrian rail mounted to the top of the concrete beam elements. The strength of these pedestrian rail elements were not considered in our strength and performance analyses for this project. For additional information, please refer to the analyses and details on the One-Line railings included in this report.

MNDOT G BARRIERS

The MnDOT Type G bridge barrier constitutes approximately 10% of the barriers used on MNDOT Bridges. Approximately 177,152 lineal feet of this barrier type is currently in service on MnDOT Bridges. The date of the earliest construction of these barrier types date back to February 1970. The latest (newest) construction of these barrier types date back to January 1977. According to MnDOT inspection records, the overall condition of the G barriers on state owned bridges were assessed to be 79.5% Good, 18.7% fair and 2.0% poor to severe. TTI has received drawings and details of the G barrier types used on MnDOT bridges. Many of the designs used a tubular steel rail element with a large angle section that anchors to the top of the concrete parapet. The strength of these tubular rail elements will be considered if they are 4 inches in diameter or greater with heavy thick wall sections. For additional information, please refer to the analyses and details on the G barriers included in this report.

1.1.1.2 MnDOT J and F Barriers

Type J and F Barriers constitute the largest percentage of barriers on MnDOT bridges. Approximately 55% (945,837 lineal feet) are currently in service. The date of the earliest construction of these barrier types date back to December 1976 (Type J). According to MnDOT inspection records, the overall condition of the J barriers on state owned bridges were assessed to be 72.1% Good, 26.7% fair and 1.3% poor to severe. TTI has received drawings and details of the J barriers. Many of the designs used since the mid 1970's use separate end posts at the ends of the barriers. The strength of these separate end posts were considered in our analyses for these two barrier types. For additional information, please refer to the analyses and details on the J barrier included in this report.

2.2 BARRIER ANALYSIS PROCEDURE

At the start of this project, TTI researchers received drawings and details for the typical J and F Barriers, One-Line railings, and G barriers from MnDOT. TTI researchers grouped the J and F Barrier types into a single category for analysis purposes. The One-Line railings were grouped into separate categories. TTI was unable to group the G barriers due to the unique features of each G barrier received from MnDOT. Therefore, all G barriers were analyzed under this task. Within each group type (J/F, and One-Line), TTI researchers sub-grouped the barriers within each group based on the common geometric features and steel reinforcement configurations. Within each sub-group of common barriers, TTI selected the most critical barrier design within each sub-group for detailed analyses and assessment with respect to MASH Specifications.

In many cases, the barrier designs with separate end posts or exhibited geometric features that were deemed critical for performance, were selected. Barrier designs with separate end posts are typically considered more critical than barrier designs with integral end posts due to the geometric features and strength of the separate end posts. The separate end posts deform discontinuously from the adjacent segment of the barrier from the crash loads used in our analyses. This discontinuity between the end post and the adjacent segment of the barrier may pose a high risk for vehicle snagging and may also inhibit the bridge barrier from properly containing and redirecting a vehicle. After reviewing the detailed drawing of each barrier, TTI determined that if a critical barrier was given a Not Satisfactory (NS) designation for the strength evaluation of the separate end post of that barrier, all other barriers in the same sub-group with a separate end post were given a NS designation for the strength evaluation of the separate end post. If there are barriers within this same sub-group that have an integral end post, the strength analysis of the separate end post for the critical barrier would not pertain to the barriers with an integral end post. If this same critical barrier satisfied all other strength evaluation criteria, the barriers within the same sub-group with integral end posts would receive an overall assessment of Satisfactory (S) for the strength evaluation criteria.

Table 2.1 through Table 2.3 present the barriers grouped and selected for detailed analyses and assessment with respect to MASH strength and performance criteria. Table 2.1 through Table 2.3 also present a summary of the analyses results for the barriers. The strength evaluation criteria column in each table is separated into an end post and barrier column. The assessment designations provided in the end post column show the results from the strength analysis of the end post. The assessment designations provided in the barrier column show the overall strength and performance results for all aspects of the barrier apart from the end post strength analysis. A Not Satisfactory designation for the overall assessment of the analyzed bridge barrier is assigned if any of the three performance criteria (barrier height, post setback, and snag potential) are given a Marginal or Not Satisfactory designation. A Satisfactory designation for the overall assessment of the analyzed barrier is assigned only if each of the three criteria are satisfied above the required or marginal conditions.

Table 2.1 J and F Barriers MASH TL-3 Summary Table.

Group	Figure Title/Bridge No.	Critical Barrier?	Barrier Height (in.)	Stability	Geometric	Strength		Overall Assessment
						End Post	Barrier	
A	Concrete and Steel Pipe Railing (Type J) With Separate End Post/5-397.112 (Appendix B1)	Y	42-5/8	S	M	NS	S	**NS**
A	Concrete and Steel Pipe Railing (Type J) With Integral End Post/5-397.113	N	42-5/8	S	M	S	S	**NS**
B	Concrete Railing (Type J) With Separate End Post (w/o wearing course)/5-397.114 (Appendix B2)	Y	32	S	S	S	S	**S**
B	Concrete Railing (Type J) With Separate End Post (w/ wearing course)/5-397.114	N	32	S	S	S	S	**S**
B	Concrete Railing (Type J) With Integral End Post (w/o wearing course)/5-397.115	N	32	S	S	S	S	**S**
C	Concrete Railing (Type J) With Separate End Post/ 5-397.116 (Appendix B3)	Y	32	S	S	NS	S	**NS**
C	Concrete Railing (Type J) With Integral End Post (w/ wearing course)/5-397.115	N	32	S	S	S	S	**S**
C	Concrete Railing (Type J) With Integral End Post/ 5-397.117	N	32	S	S	S	S	**S**
C	Concrete Railing (Type J) With Integral End Post/19056 (5-397.117)	N	32	S	S	S	S	**S**
C	Concrete Railing (Type J) With Integral End Post (South Railing)/19042 (5-397.120)	N	32	S	S	S	S	**S**
C	Concrete Railing (Type J) With Separate End Post (North Railing)/19042 (5-397.120)	N	32	S	S	NS	S	**NS**
D	Concrete Railing (Type J-SW) With Sidewalk And Separate End Post/5-397.118 (Appendix B4)	Y	46	S	S	NS	S	**NS**

	Concrete Railing (Type J-SW) With Sidewalk And Integral End Post/5-397.119	N	36	S	S	S	S	**S**
E	Concrete Railing (Type J) With Bridge Slab Sidewalk And Separate End Post/5-397.121 (Appendix B5)	Y	42	S	S	NS	S	**NS**
	Concrete Railing (Type J) With Bridge Slab Sidewalk And Integral End Post/5-397.122	N	42	S	S	S	S	**S**
	Concrete Railing (Type J) With Bridge Slab Sidewalk And Separate End Post (w/o wearing course)/5-397.123	N	44	S	S	NS	S	**NS**
F	Precast Concrete Railing (Type J) With Integral End Post (w/o wearing course)/5-397.141 (Appendix B6)	Y	32	S	S	S	S	**S**
	Precast Concrete Railing (Type J) With Integral End Post (w/ wearing course)/5-397.140	N	32	S	S	S	S	**S**
G	Concrete and Fence Railing (Type J)/Bridge No. 62828 (5-397.120) (w/ Vertical Wall) (Appendix B7)	Y	32	S	NS	S	S	**NS**
	Bikeway Railing Concrete (Type J) and Fence Integral Post no Sidewalk (w/ wearing course)/Bridge No. 62828 (5-397.156)	N	32	S	NS	S	S	**NS**
H	Concrete Barrier (Type F) With Separate End Post (w/o wearing course)/Figure 5-397.114 (Appendix B8)	Y	32	S	S	S	S	**S**
	Concrete Barrier (Type F) With Integral End Post (w/o wearing course)/Figure 5-397.115	N	32	S	S	S	S	**S**
	Concrete Barrier (Type F) With Separate End Post (w/ wearing course)/Figure 5-397.116	N	32	S	S	S	S	**S**
	Concrete Barrier (Type F) With Integral End Post (w/ wearing course)/Figure 5-397.117	N	32	S	S	S	S	**S**
	Concrete Barrier (Type F) With Integral End Post (w/ wearing course)/Figure 5-397.122	N	42	S	S	S	S	**S**

Y = Yes / N = No / S = Satisfactory / M = Marginal / NS = Not Satisfactory

Table 2.2 One-Line Railings MASH TL-3 Summary Table.

Group	Figure Title/No.	Critical Barrier?	Barrier Height (in.)	Stability	Geometric	Strength		Overall Assessment
						End Post	Barrier	
A	Concrete Railing for 6” Brush Curb With End Post/5-397.102 (Appendix C1)	Y	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing for 6” Brush Curb Without End Post/5-397.101	N	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing For West Curb/ Bridge No.27177	N	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing for 6” Brush Curb/ Bridge No.62040	N	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing for 6” Brush Curb/ Bridge No.59002	N	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing for 6” High Curb/ Bridge No.73820	N	34	S	NS	NS	NS	**NS**
	Concrete Railing for 6” Brush Curb With End Post/Bridge No. 30505 (5-397.102)	N	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing for 6” Brush Curb/ Bridge No. 25505	N	34-1/4	S	NS	NS	NS	**NS**
	Concrete Railing for 6” Brush Curb/ Bridge No.43008	N	34-1/4	S	NS	NS	NS	**NS**
B	Concrete Railing for 10” High Curb/ Bridge No.70802 (Appendix C2)	Y	38-1/4	S	NS	-	NS	**NS**
C	Concrete Railing for 10” High Curb/ Bridge No.21809 (Appendix C3)	Y	38-1/4	S	NS	-	NS	**NS**
	Concrete Railing for 10” High Curb/ Bridge No.82804	N	38-1/4	S	NS	-	NS	**NS**
D	Concrete railing With Cable and Pipe/ Bridge No.69834 (Appendix C4)	Y	28	NS	NS	-	NS	**NS**
E	Concrete railing With Cable and Pipes With End Post/5-397.104 (Appendix C5)	Y	28	NS	NS	NS	NS	**NS**

	Concrete railing With Cable and Pipes Without End Post/5-397.103	N	28	NS	NS	NS	NS	**NS**
	Concrete railing With Cable and Pipes With End Post/ Bridge No.62069	N	28	NS	NS	NS	NS	**NS**

Y = Yes / N = No / S = Satisfactory / M = Marginal / NS = Not Satisfactory

Table 2.3 G Barrier MASH TL-3 Summary Table.

Figure Title/No.	Barrier Height (in.)	Stability	Geometrics	Strength		Overall Assessment
				End Post	Barrier	
Ornamental Metal Railing One Line (Type G)/ Bridge No. 09830 (5-397.107) (Appendix D1)	40-5/8	S	M	S	S	**NS**
Concrete Railing (Type G) with Pipe and Integral End Post/ Bridge No. 19021 (5-397.109) (Appendix D2)	40-5/8	S	M	S	S	**NS**
Concrete Railing (Type G) with Pipe and Separate End Post/ Bridge No. 86812 (5-397.107) (Appendix D2)	40-5/8	S	M	S	S	**NS**

The analysis of the barriers was performed in accordance with the American Association of State Highways and Transportation Officials (AASHTO) Load and Resistance Factor Bridge Design Specifications, 2017 8th Edition (ref. 2). In addition, information from NCHRP Project 20-07/Task 395 (ref. 3) was used to evaluate the bridge barriers considered for analyses with respect to current MASH performance specifications.

To evaluate the critical barriers according to MASH performance specifications, three different criteria were considered. These criteria consist of stability, rail geometrics, and strength. The analysis methodologies used to evaluate these criteria are presented below. The results of the analyses were used to determine which barriers can be considered MASH compliant and which will require further analysis or crash testing to establish MASH compliance.

2.2.1 Stability Requirements for MASH Bridge Barriers

For a bridge barrier to be considered a MASH acceptable barrier, a minimum height must be met to ensure stability of the vehicle. Table 2.4 shows the minimum height requirements for MASH TL-2, TL-3 and TL-4 bridge barriers.

Table 2.4 Minimum Height Requirements for MASH TL-2, TL-3, and TL-4.

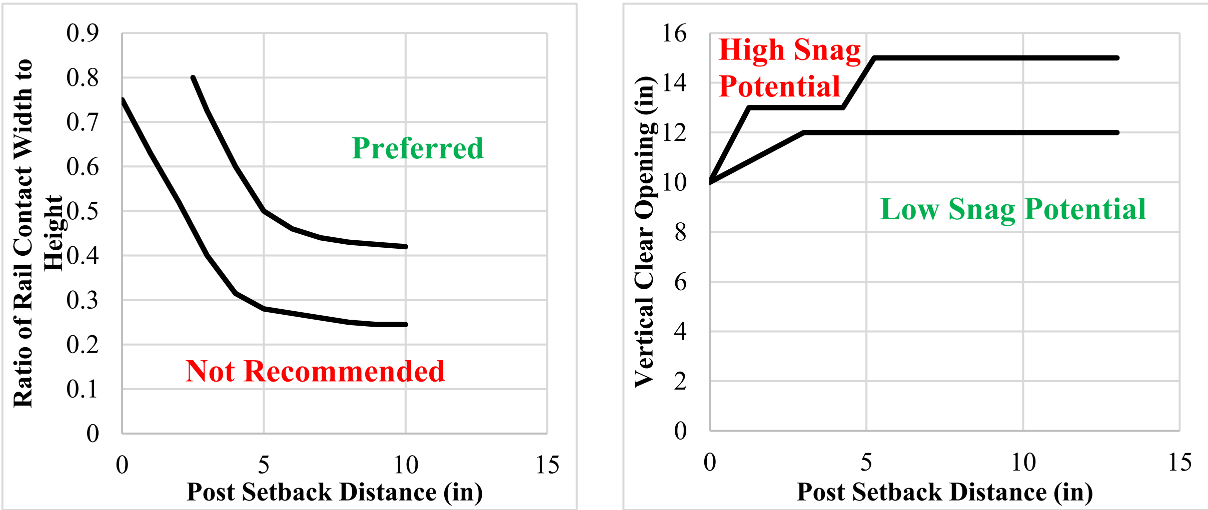
MASH Test Level	Minimum Height (in.)
TL-2	18(2)
TL-3	29(3)
TL-4	36(4)

(4) NCHRP Project 22-20(2) (ref. 4)

The height of a barrier being analyzed was acquired from the detailed drawings of that specific barrier and compared to the minimum height requirement for the specified test level. As specified in AASHTO Section 13 LRFD, barrier height is measured from the top of the roadway surface or wearing course thickness to the top of the barrier. If the minimum barrier height was satisfied, the barrier was considered to satisfactorily meet stability requirements.

2.2.2 Geometric Requirements for MASH Bridge Barriers

The geometric relationships for bridge barriers contained in the current Section 13 *AASHTO LRFD Bridge Design Specifications* (Figure 2-2) were applied to evaluate barrier geometry. These relationships pertain to the potential for wheel, bumper or hood snagging on elements of the bridge barrier. Severe snagging can lead to a number of undesirable consequences including increased occupant compartment deformation, higher accelerations and occupant risk indices, and vehicle instability. Both AASHTO figures are used to analyze barrier geometry for all MASH Test Levels.



(a) Post Setback Criteria (b) Snag Potential Criteria

Figure 2-2 AASHTO Section 13 Figures A13.1.1-2 and A13.1.1-3 for all MASH Test Levels.

For a barrier to be given a Satisfactory (S) designation for the geometric evaluation criteria, the barriers' geometric data points (i.e., post setback distance, rail contact width to height ratio, and vertical clear opening) must plot in the AASHTO Figure A13.1.1-2 and A13.1.1-3 acceptable regions. The Preferred region in AASHTO Figure A13.1.1-2 and the Low Snag Potential region in AASHTO Figure A13.1.1-3 are considered the acceptable regions. A barrier is given a Marginal (M) designation for the geometric evaluation criteria if the barriers' geometric data points plots between the Preferred and Not Recommended regions (Figure A13.1.1-2) or the Low Snag Potential and High Snag Potential regions (Figure A13.1.1-3). A barrier is given a Not Satisfactory (NS) designation for the geometric evaluation criteria if the barriers' geometric data points plot in the Not Recommended region (Figure A13.1.1-2) or the High Snag Potential region (Figure A13.1.1-3).

The potential for snagging causing occupant risk exceeding the MASH thresholds, along with vehicle stability, have been evaluated through previous testing of the New Jersey Safety Shape (NJSS) concrete barrier and the T224 barrier. NJSS barriers have a profile similar to the J barriers used by MnDOT and evaluated herein. F-shaped concrete barriers have a profile similar to the F barriers used by MnDOT and evaluated herein. While no MASH Test 3-10 or MASH Test 3-11 has been conducted on a F-Shaped concrete barrier, the cross-sectional profile of the NJSS is considered more critical in terms of vehicle stability and the T224 barrier, which has a vertically aligned traffic face, is considered more critical in terms of vehicle decelerations. MASH Test 3-10 and MASH Test 3-11 were successfully performed on the NJSS barrier (ref. 5,6). MASH Test 5-10 and MASH Test 5-11 were successfully performed on the T224 barrier (ref. 7). Therefore, the potential for occupant risk exceeding the MASH thresholds for the pickup truck and small car, and vehicle stability are acceptable for the J and F Barriers that do not have structural steel post and metal rail attachments. However, for the barriers that do have metal rail attachments, the tables provided in AASHTO Section 13 geometric criteria were used to evaluate the potential for snagging and high occupant risk. For each One-Line bridge rail and G barrier analyzed, post setback distance, ratio of contact width to height, and vertical clear opening were determined or calculated from the provided bridge barrier details and plotted against the current AASHTO LRFD Section 13 geometric criteria.

2.2.3 Strength Requirements for MASH Bridge Barriers

Section 13 of the *AASHTO LRFD Bridge Design Specifications* contains procedures for analyzing the structural capacity of different types of bridge barriers (e.g., steel, concrete). These procedures were used to evaluate the strength of the selected barriers for this project. Using these procedures, an analysis of the strength of the selected barriers was performed using updated loads for MASH Test Level 3 impact conditions. All barriers analyzed for this project were evaluated with respect to current recommended MASH TL-3 impact loading conditions [(3)]. For a G barrier, the strength of the metal rails, posts, and post connections were analyzed to obtain the overall strength of the barrier system.

2.3 MNDOT BARRIER ANALYSES

The analyses procedures described in the previous section were applied to the barriers considered for this project and shown in Table 2.1 through Table 2.3 above. The results of each barrier analysis are summarized in the sections below. The loading conditions used in the analyses for this project are provided in Table 2.5 below. This information was used for all bridge barriers analyzed and reported in NCHRP Project 20-07/Task 395 (ref. 3). Table 2.5 is an excerpt from this research project.

Table 2.5 Design Forces for Traffic Railings.

Test Level	**Rail Height** (in.)	**F_t** (kip)	**F_L** (kip)	**F_v** (kip)	**L_t and L_L** (ft)	**L_v** (kip)	**H_e** (in.)	**H_{min}** (in.)
TL-1(2)	18 or above	13.5	4.5	4.5	4.0	18.0	18.0	18.0
TL-2(2)	18 or above	27.0	9.0	4.5	4.0	18.0	20.0	18.0
TL-3(3)	29 or above	71.0	18.0	4.5	4.0	18.0	19.0	29.0
TL-4 (a)(4)	36	68.0	22.0	38.0	4.0	18.0	25.0	36.0
TL-4 (b)(4)	greater than 36	80.0	27.0	22.0	5.0	18.0	30.0	36.0
TL-5 (a)(4)	42	160.0	41.0	80.0	10.0	40.0	35.0	42.0
TL-5 (b)(4)	greater than 42	262.0	75.0	160.0	10.0	40.0	43.0	42.0
TL 6(2)	90 or above	175.0	58.0	80.0	8.0	40.0	56.0	90.0

Note: (2)AASHTO LRFD Section 13 Table A13.2-1; (3)NCHRP Project 20-07/Task 395; (4)NCHRP Project 22-20(2)

2.3.1 J and F Barriers

2.3.1.1 J Barrier on Figure 5-397.112 (Appendix B1)

The J barrier on Figure 5-397.112 is a metal post and beam system mounted on a J barrier, with a separate end post that is 18 inches long. Appendix B1 contains the details and full analysis for the J barrier on Figure 5-397.112. Figure 2-3 shows a detailed view of the J barrier on Figure 5-397.112. Below is a summary of the evaluation results and recommendations.

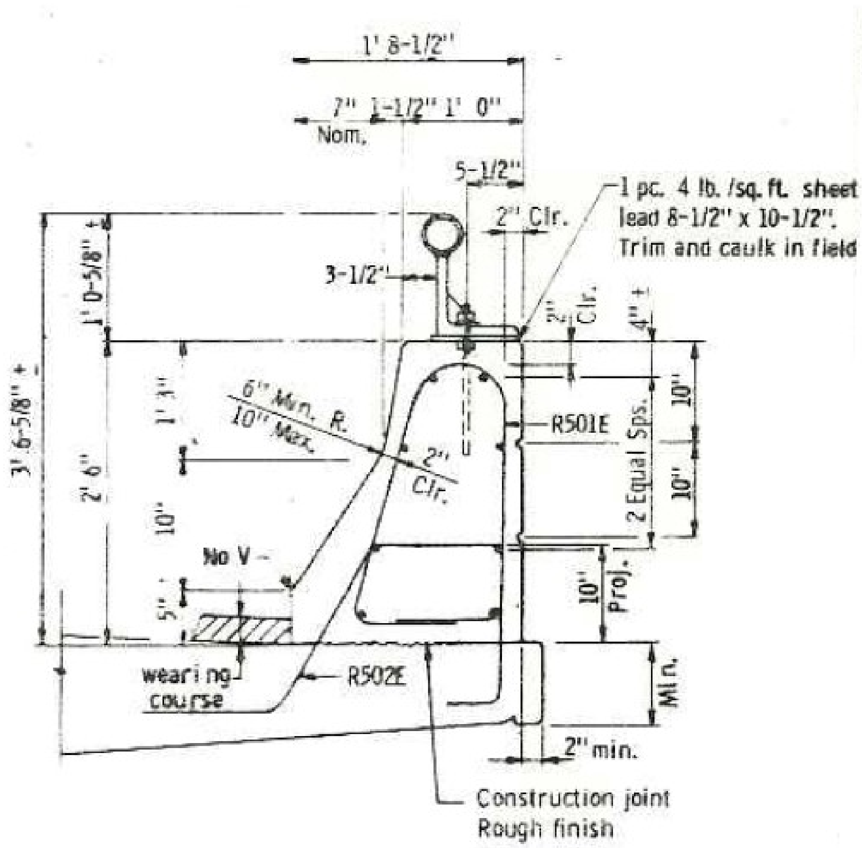


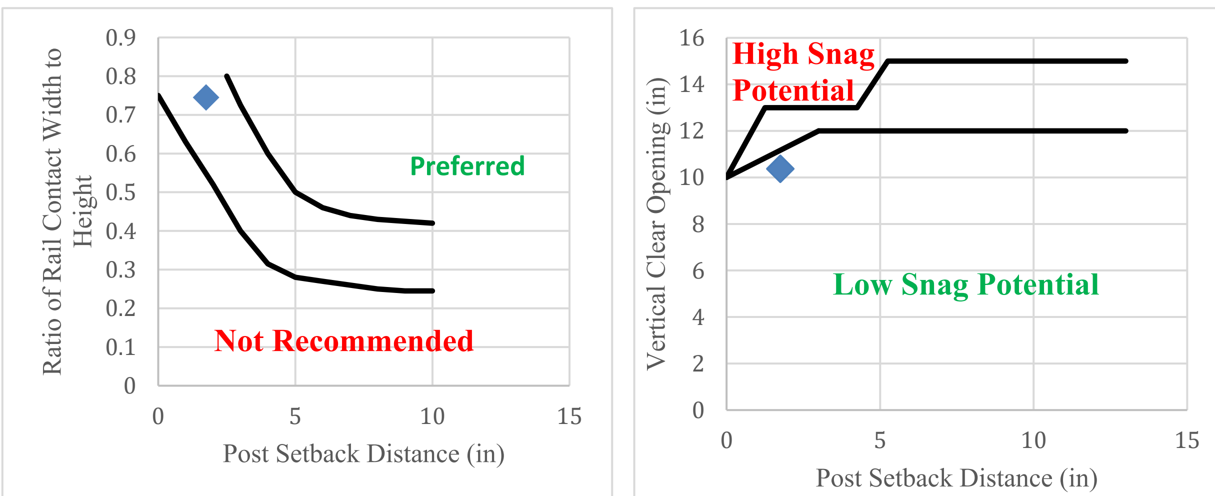
Figure 2-3 Detailed View of J Barrier on Figure 5-397.112.

STABILITY EVALUATION

The J barrier on Figure 5-397.112 has a height of 42-5/8 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. The J barrier on Figure 5-397.112 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the J barrier on Figure 5-397.112. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-4, the barriers' geometric data points plot in the marginal region for the Post Setback criteria and in the acceptable region for the Snag Potential criteria. Therefore, the J barrier on Figure 5-397.112 does not satisfy the geometric evaluation criteria (Marginal).



(a) Post Setback Criteria

(b) Snag Potential Criteria

Figure 2-4 Geometric Criteria Assessment of the J Barrier on Figure 5-397.112.

STRENGTH EVALUATION

The structural capacity of the J barrier on Figure 5-397.112 was compared to the current recommended MASH TL-3 design transverse impact load provided in Table 2.5. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.6 presents the results from the strength analysis conducted for the J barrier on Figure 5-397.112. As summarized in Table 2.6, the J barrier on Figure 5-397.112 does not meet MASH TL-3 structural adequacy criterion due to a lack of strength in the separate end post (Not Satisfactory).

Table 2.6 Summary of MASH TL-3 Strength Analysis for the J Barrier on Figure 5-397.112.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	230 kips	**Satisfactory**
Structural Capacity of the Barrier at a Post	71 kips	228 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	50 kips	**Not Satisfactory**

RECOMMENDATION

As summarized in Table 2.7, the J barrier on Figure 5-397.112 does not satisfy all MASH TL-3 evaluation criteria.

The assessment of occupant risk is not considered satisfactory due to the barrier geometrics plotting in the marginal region for the post setback criteria (see Figure 2-4). Therefore, TTI recommends that modifications be made to the J barrier on Figure 5-397.112 to satisfy the MASH geometric evaluation criteria.

The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of structural capacity in the separate end post for the J barrier on Figure 5-397.112 (see Table 2.6). All aspects of the barrier that do not involve the end post satisfy MASH TL-3 structural adequacy criterion. Therefore, TTI recommends that modifications be made to the separate end post for the J barrier on Figure 5-397.112 to satisfy MASH TL-3 structural adequacy criterion.

Table 2.7 Summary of MASH TL-3 Assessment of J Barrier on Figure 5-397.112.

	Required	Actual	Assessment
Stability	29 in.	42-5/8 in.	**Satisfactory**
Geometric	See Figure 2-4		**Marginal**
Strength	See Table 2.6		**Not Satisfactory**

2.3.1.2 J Barrier on Figure 5-397.114 (Appendix B2)

The J barrier on Figure 5-397.114 is a concrete bridge barrier with a separate concrete end post that has a minimum length of 3'- 0". Appendix B2 contains the details and full analysis for the J barrier on Figure 5-397.114. Figure 2-5 shows a detailed view of the J barrier on Figure 5-397.114. Below is a summary of the evaluation results and recommendations.

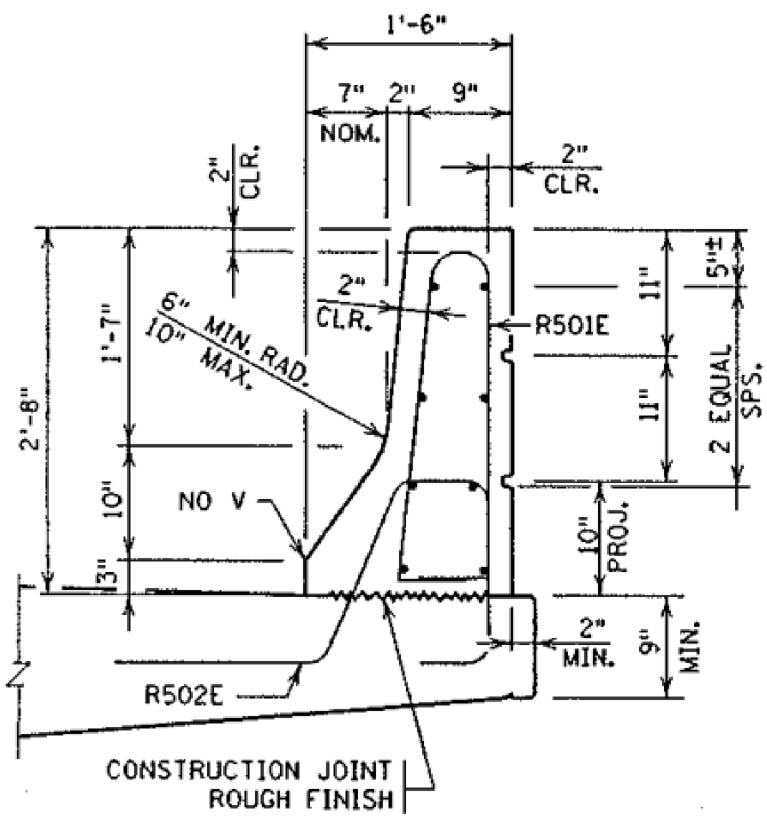


Figure 2-5 Detailed View of J barrier on Figure 5-397.114.

STABILITY EVALUATION

The J barrier on Figure 5-397.114 has a height of 32 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the J barrier on Figure 5-397.114 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on concrete barriers have shown that the profile of a J barrier is acceptable for MASH TL-3. This barrier does not have a metal rail attachment and therefore, the geometric data points for the J barrier on Figure 5-397.114 were not determined and the assessment of occupant risk is considered satisfactory (Satisfactory).

STRENGTH EVALUATION

The structural capacity of the J barrier on Figure 5-397.114 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.8 presents the results from the strength analysis conducted for the J barrier on Figure 5-397.114. As summarized in Table 2.8, the J barrier on Figure 5-397.114 meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.8 Summary of MASH TL-3 Strength Analysis for J Barrier on Figure 5-397.114.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	153 kips	**Satisfactory**
Structural Capacity of the Barrier at the End/Joints	71 kips	115 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	77 kips	**Satisfactory**
Structural Capacity of the End Post and the End of the Barrier	71 kips	141 kips	**Satisfactory**
Shear Capacity of the Barrier	71 kips	80 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.9, the J barrier on Figure 5-397.114 satisfies MASH TL-3 criteria.

Table 2.9 Summary of MASH TL-3 Assessment of J Barrier on Figure 5-397.114.

	Required	Actual	Assessment
Stability	29 in.	32 in.	**Satisfactory**
Geometric	–		**Satisfactory**
Strength	See Table 2.8		**Satisfactory**

2.3.1.3 J Barrier on Figure 5-397.116 (Appendix B3)

The J barrier on Figure 5-397.116 is a concrete bridge barrier with a 2'- 0" long separate concrete end post. A 2-inch thick wearing course was included in the analysis for this barrier. Appendix B3 contains the details and full analysis for the J barrier on Figure 5-397.116. Figure 2-6 shows a detailed view of the J barrier on Figure 5-397.116. Below is a summary of the evaluation results and recommendations.

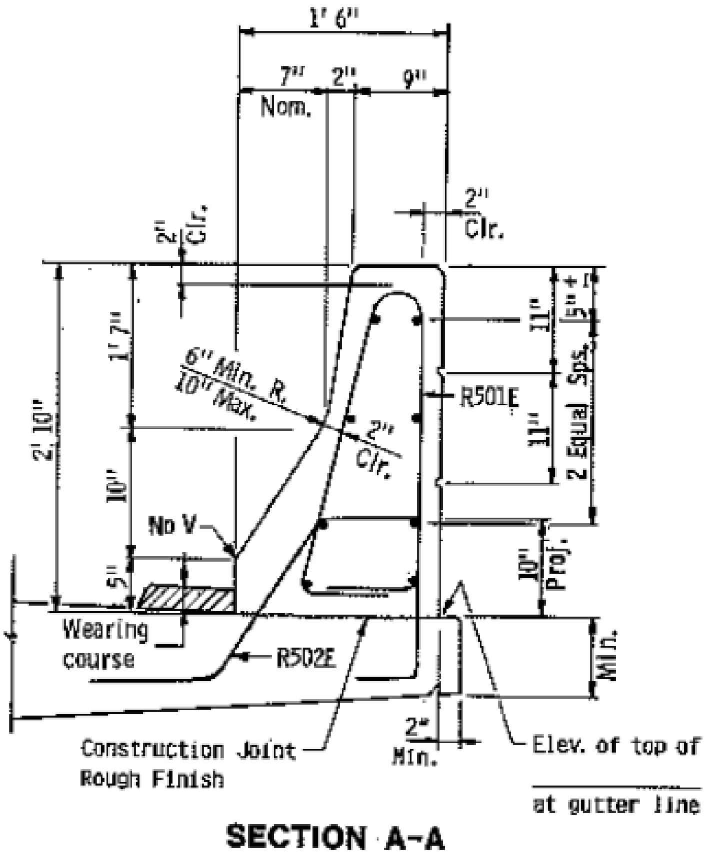


Figure 2-6 Detailed View of JBarrier on Figure 5-397.116.

STABILITY EVALUATION

The J barrier on Figure 5-397.116 has a height of 32 inches measured from the top of a 2-inch thick overlay. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the J barrier on Figure 5-397.116 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on similar shape concrete barriers (Jersey Shape) have shown that the profile of this J barrier is acceptable for MASH TL-3. The barrier does not have a metal rail attachment and therefore, the geometric data points for the J barrier on Figure 5-397.116 were not determined and the assessment of occupant risk is considered satisfactory (Satisfactory).

STRENGTH EVALUATION

The structural capacity of the J barrier on Figure 5-397.116 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.10 presents the results from the strength analysis conducted for the J barrier on Figure 5-397.116. As summarized in Table 2.10, the J barrier on Figure 5-397.116 does not meet MASH TL-3 structural adequacy criterion due to a lack of strength in the 2' - 0" long separate end post (Not Satisfactory).

Table 2.10 Summary of MASH TL-3 Strength Analysis for J Barrier on Figure 5-397.116.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	151 kips	**Satisfactory**
Structural Capacity of the Barrier at Ends	71 kips	83 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	52 kips	**Not Satisfactory**
Shear Capacity of the Barrier	71 kips	81 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.11, the J barrier on Figure 5-397.116 does not satisfy all MASH TL-3 criteria. The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of structural capacity in the separate end post for the J barrier on Figure 5-397.116 (see Table 2.10). All aspects of the barrier that do not involve the end post satisfy MASH TL-3 structural adequacy criterion. Therefore, TTI recommends that modifications, to be determined, be made to the separate end post for the J barrier on Figure 5-397.116 to satisfy MASH TL-3 structural adequacy criterion.

Table 2.11 Summary of MASH TL-3 Assessment of J Barrier on Figure 5-397.116.

	Required	Actual	Assessment
Stability	29 in.	32 in.	**Satisfactory**
Geometric	–		**Satisfactory**
Strength	See Table 2.10		**Not Satisfactory**

2.3.1.4 J Barrier on Figure 5-397.118 (Appendix B4)

The J barrier on Figure 5-397.118 is a concrete bridge barrier with a 2'- 0" long separate concrete end post. A 2-inch thick wearing course was considered in the analysis for this barrier. Appendix B4 contains the details and full analysis for the J barrier on Figure 5-397.118. Figure 2-7 shows a detailed view of the J barrier on Figure 5-397.118. Below is a summary of the evaluation results and recommendations.

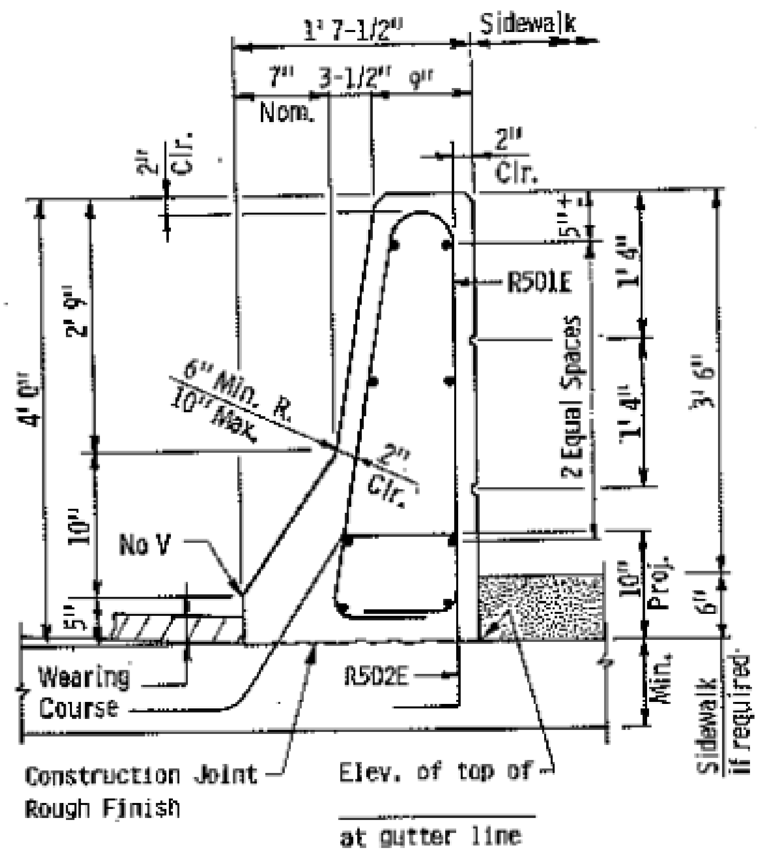


Figure 2-7 Detailed View of J Barrier on Figure 5-397.118.

STABILITY EVALUATION

The J barrier on Figure 5-397.118 has a height of 46 inches measured from the top of a 2-inch thick overlay. The minimum h eight requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the J barrier on Figure 5-397.118 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on concrete barriers have shown that the profile of a J barrier is acceptable for MASH TL-3. This barrier does not have a metal rail attachment and therefore, the geometric data points for the J barrier on Figure 5-397.118 were not determined and the assessment of occupant risk is considered satisfactory (Satisfactory).

STRENGTH EVALUATION

The structural capacity of the J barrier on Figure 5-397.118 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.12 presents the results from the strength analysis conducted for the J barrier on Figure 5-397.118. As summarized in Table 2.12, the J barrier on Figure 5-397.118 does not meet MASH TL-3 structural adequacy criterion due to lack of strength in the 2’- 0” long separate end post (Not Satisfactory).

Table 2.12 Summary of MASH TL-3 Strength Analysis for J Barrier on Figure 5-397.118.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	195 kips	**Satisfactory**
Structural Capacity of the Barrier at Ends	71 kips	114 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	52 kips	**Not Satisfactory**
Shear Capacity of the Barrier	71 kips	81 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.13, the J barrier on Figure 5-397.118 does not satisfy all MASH TL-3 criteria. The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of structural capacity in the separate end post for the J barrier on Figure 5-397.118 (see Table 2.12). All other aspects of the barrier that do not involve the end post satisfy MASH TL-3 structural adequacy criterion. Therefore, TTI recommends that modifications be made to the separate end post for the J barrier on Figure 5-397.118 to satisfy MASH TL-3 structural adequacy criterion.

Table 2.13 Summary of MASH TL-3 Assessment of J Barrier on Figure 5-397.118.

	Required	Actual	Assessment
Stability	29 in.	46 in.	**Satisfactory**
Geometric	–		**Satisfactory**
Strength	See Table 2.12		**Not Satisfactory**

2.3.1.5 J Barrier on Figure 5-397.121 (Appendix B5)

The J barrier on Figure 5-397.121 is a concrete bridge barrier with a 2'- 0" long separate concrete end post. A 2-inch thick wearing course was considered in the analysis for this barrier. Appendix B5 contains the details and full analysis for the J barrier on Figure 5-397.121. Figure 2-8 shows a detailed view of the J barrier on Figure 5-397.121. Below is a summary of the evaluation results and recommendations.

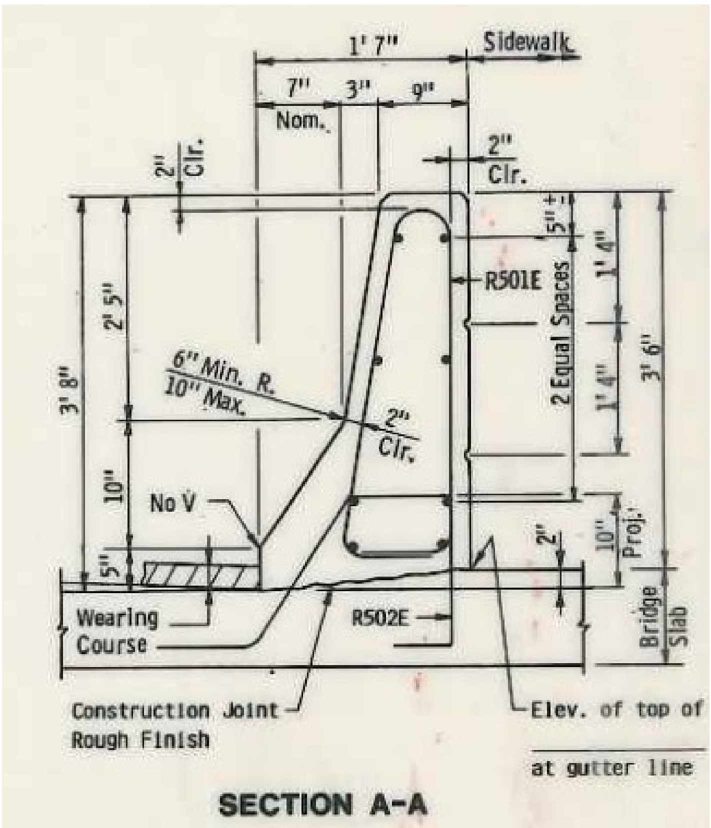


Figure 2-8 Detailed View of J Barrier on Figure 5-397.121.

STABILITY EVALUATION

The J barrier on Figure 5-397.121 has a height of 42 inches measured from the top of a 2-inch thick overlay. The minimum height requirement for a MASH TL-3 bridge barrier system is 29 inches. Therefore, the J barrier on Figure 5-397.121 meets the MASH TL-3 stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on concrete barriers have shown that the profile of a J barrier is acceptable for MASH TL-3. This barrier does not have a metal rail attachment and therefore, the geometric data points for the J barrier on Figure 5-397.121 were not determined and the assessment of occupant risk is considered satisfactory (Satisfactory).

STRENGTH EVALUATION

The structural capacity of the J barrier on Figure 5-397.121 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface.Table 2.14 presents the results from the strength analysis conducted for the J barrier on Figure 5-397.121. As summarized in Table 2.14, the J barrier on Figure 5-397.121 does not meet MASH TL-3 structural adequacy criterion due to a lack of strength of the 2'- 0" long separate end post (Not Satisfactory).

Table 2.14 Summary of MASH TL-3 Strength Analysis for J Barrier on Figure 5-397.121.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	181 kips	**Satisfactory**
Structural Capacity of the Barrier at Ends	71 kips	95 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	47 kips	**Not Satisfactory**
Shear Capacity of the Barrier	71 kips	81 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.15, the J barrier on Figure 5-397.121 does not satisfy all MASH TL-3 criteria. The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of structural capacity in the separate end post for the J barrier on Figure 5-397.121 (see Table 2.14). Therefore, TTI recommends that modifications be made to the separate end post for the J barrier on Figure 5-397.121 to satisfy MASH TL-3 structural adequacy criterion. All aspects of the barrier that do not involve the end post satisfy MASH TL-3 structural adequacy criterion.

Table 2.15 Summary of MASH TL-3 Assessment of J Barrier on Figure 5-397.121.

	Required	Actual	Assessment
Stability	29 in.	42 in.	**Satisfactory**
Geometric	-		**Satisfactory**
Strength	See Table 2.14		**Not Satisfactory**

2.3.1.6 J Barrier on Figure 5-397.141 (Appendix B6)

The J barrier on Figure 5-397.141 is a concrete bridge barrier. Appendix B6 contains the details and full analysis for the J barrier on Figure 5-397.141. Figure 2-9 shows a detailed view of the J barrier on Figure 5-397.141. Below is a summary of the evaluation results and recommendations.

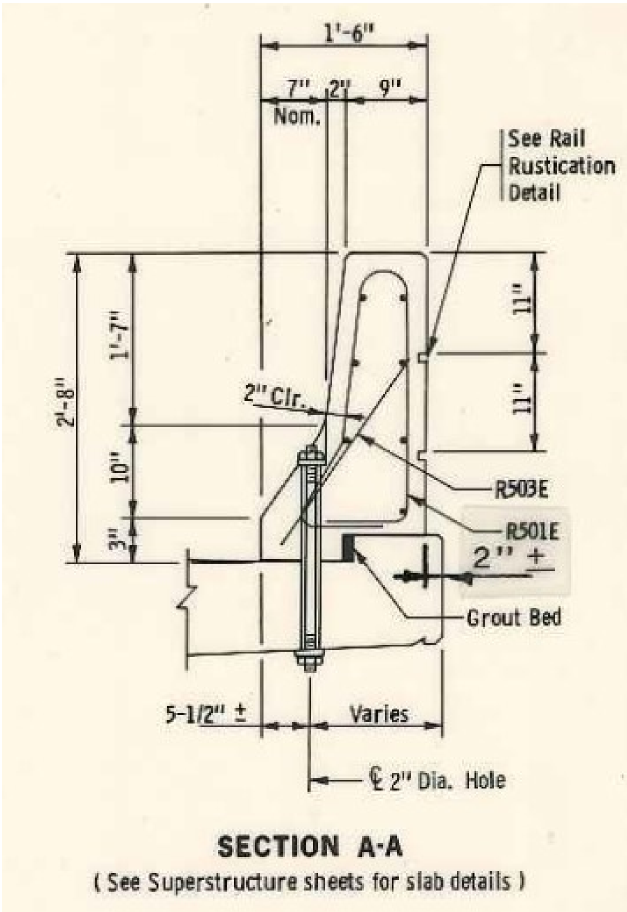


Figure 2-9 Detailed View of J Barrier on Figure 5-397.141.

STABILITY EVALUATION

The J barrier on Figure 5-397.141 has a height of 32 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the J barrier on Figure 5-397.141 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on concrete barriers have shown that the profile of a J barrier is acceptable for MASH TL-3. This barrier does not have a metal rail attachment and therefore, the geometric data points for the J barrier on Figure 5-397.141 were not determined and the assessment of occupant risk is considered satisfactory (Satisfactory).

STRENGTH EVALUATION

The structural capacity of the J barrier on Figure 5-397.141 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.16 presents the results from the strength analysis conducted for the J barrier on Figure 5-397.141. As summarized in Table 2.16, the J barrier on Figure 5-397.141 meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.16 Summary of MASH TL-3 Strength Analysis for J Barrier on Figure 5-397.141.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	158 kips	**Satisfactory**
Structural Capacity of the Barrier at the End/Joints	71 kips	105 kips	**Satisfactory**
Structural Capacity of the End Post and the Conjoining End Segment	71 kips	105 kips	**Satisfactory**
Shear Capacity of the Barrier	71 kips	80 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.17, the J barrier on Figure 5-397.141 satisfies MASH TL-3 criteria.

Table 2.17 Summary of MASH TL-3 Assessment of J Barrier on Figure 5-397.141.

	Required	Actual	Assessment
Stability	29 in.	32 in.	**Satisfactory**
Geometric	–		**Satisfactory**
Strength	See Table 2.16		**Satisfactory**

2.3.1.7 J Barrier on Bridge No. 62828 (Figure 5-397.156 Modified) (Appendix B7)

The J barrier on Bridge No. 62828 (Figure 5-397.156 modified) is a concrete bridge barrier with a chain link fence mounted on top. Appendix B7 contains the details and full analysis for the J barrier on Bridge No. 62828 (Figure 5-397.156 modified). Figure 2-10 shows a detailed view of the J barrier on Bridge No. 62828 (Figure 5-397.156 modified). Below is a summary of the evaluation results and recommendations.

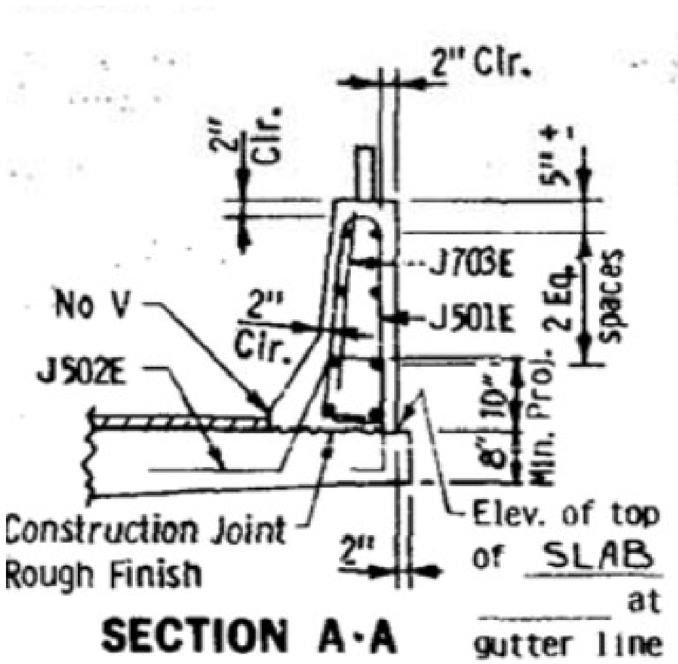


Figure 2-10 Detailed View of J Barrier on Bridge No. 62828 (Figure 5-397.156 modified).

STABILITY EVALUATION

The J barrier on Bridge No. 62828 (Figure 5-397.156 modified) has a height of 32 inches measured from the top of a 2-inch thick overlay. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the J barrier on Bridge No. 62828 (Figure 5-397.156 modified) meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on concrete barriers have shown that the profile of a J barrier is acceptable for MASH TL-3. The chain link fence mounted to the top of the J barrier has not been evaluated through full-scale crash testing. At the time of this writing, the performance of the fence anchored to the top of the J barrier is uncertain with respect to MASH. Full-scale crash testing is warranted for this design. Therefore, the performance of this barrier with respect to MASH TL-3 is uncertain at this time due to the chain link fence mounted to the top of the barrier and full-scale crash testing of this design is required to evaluate the J barrier on Bridge No. 62828 (Figure 5-397.156 modified) for MASH TL-3 compliance (Not Satisfactory).

STRENGTH EVALUATION

The structural capacity of the J barrier on Bridge No. 62828 (Figure 5-397.156 modified) was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.18 presents the results from the strength analysis conducted for the J barrier on Bridge No. 62828 (Figure 5-397.156 modified). As summarized in Table 2.18, the J barrier on Bridge No. 62828 (Figure 5-397.156 modified) meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.18 Summary of MASH TL-3 Strength Analysis for J Barrier on Bridge No. 62828 (Figure 5-397.156 modified).

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	159 kips	**Satisfactory**
Structural Capacity of the Barrier at the End/Joints	71 kips	106 kips	**Satisfactory**
Structural Capacity of the End Post and the Conjoining End Segment	71 kips	184 kips	**Satisfactory**
Shear Capacity of the Barrier	71 kips	81 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.19, the J barrier on modified Figure 5-397-156 does not satisfy all MASH TL-3 criteria. The assessment of occupant risk is not considered satisfactory due to the chain link fence mounted on top of the barrier. Full-scale crash testing of this design is required to evaluate the J barrier on Bridge No. 62828 (Figure 5-397.156 modified) for MASH TL-3 compliance.

Table 2.19 Summary of MASH TL-3 Assessment of J Barrier on Bridge No. 62828 (Figure 5-397.156 modified).

	Required	Actual	Assessment
Stability	29 in.	32 in.	**Satisfactory**
Geometric	–		**Not Satisfactory**

Strength	See Table 2.18	**Satisfactory**

2.3.1.8 F Barrier on Figure 5-397.114 (Appendix B8)

The F barrier on Figure 5-397.114 is a concrete bridge barrier with a 3'- 0" long separate concrete end post. Appendix B8 contains the details and full analysis for the F barrier on Figure 5-397.114. Figure 2-11 shows a detailed view of the F barrier on Figure 5-397.114. Below is a summary of the evaluation results and recommendations.

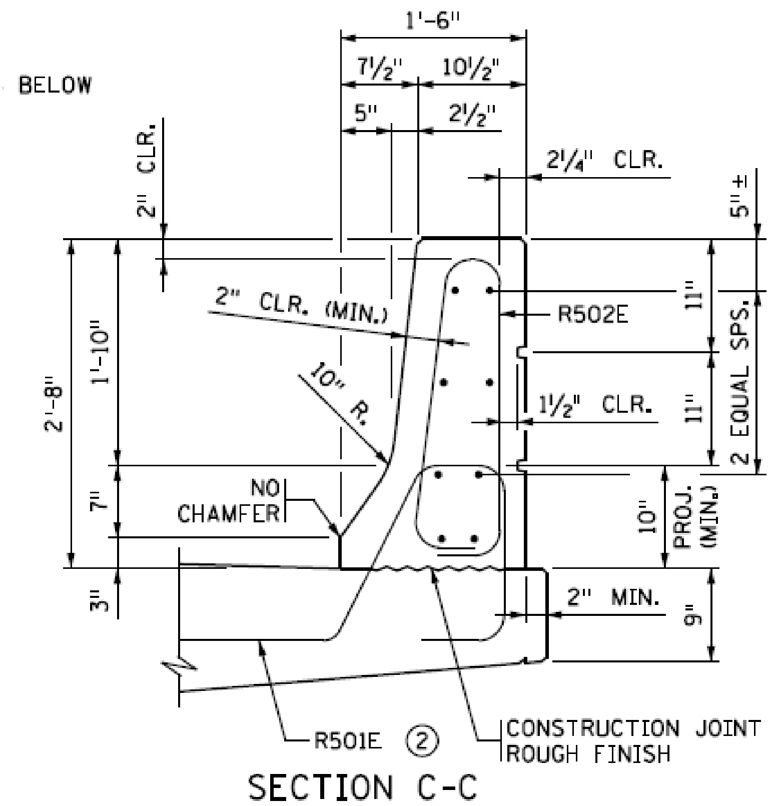


Figure 2-11 Detailed View of F Barrier on Figure 5-397.114.

STABILITY EVALUATION

The F barrier on Figure 5-397.114 has a height of 32 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the F barrier on Figure 5-397.114 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Previous full-scale crash tests on concrete barriers have shown that the profile of a F barrier is acceptable for MASH TL-3. This barrier does not have metal rail attachments and therefore, the geometric data points for the F barrier on Figure 5-397.114 were not determined and the assessment of occupant risk is considered satisfactory (Satisfactory).

STRENGTH EVALUATION

The structural capacity of the F barrier on Figure 5-397.114 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.20 presents the results from the strength analysis conducted for the F barrier on Figure 5-397.114. As summarized in Table 2.20, the F barrier on Figure 5-397.114 meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.20 Summary of MASH TL-3 Strength Analysis for F Barrier on Figure 5-397.114.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	193 kips	**Satisfactory**
Structural Capacity of the Barrier at Ends	71 kips	128 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	90 kips	**Satisfactory**
Shear Capacity of the Barrier	71 kips	81 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.21, the F barrier on Figure 5-397.114 satisfies MASH TL-3 criteria.

Table 2.21 Summary of MASH TL-3 Assessment of F Barrier on Figure 5-397.114.

	Required	Actual	Assessment
Stability	29 in.	32 in.	**Satisfactory**
Geometric	–		**Satisfactory**
Strength	See Table 2.20		**Satisfactory**

2.3.2 One-Line Railings

2.3.2.1 One-Line Bridge Rail on Figure 5-397.102 (Appendix C1)

The One-Line Bridge Rail on Figure 5-397.102 is a concrete post and beam system with an 18-inch long separate concrete end post. Appendix C1 contains the details and full analysis for the One-Line Bridge Rail on Figure 5-397.102. Figure 2-12 shows a detailed view of the One-Line Bridge Rail on Figure 5-397.102. Below is a summary of the evaluation results and recommendations.

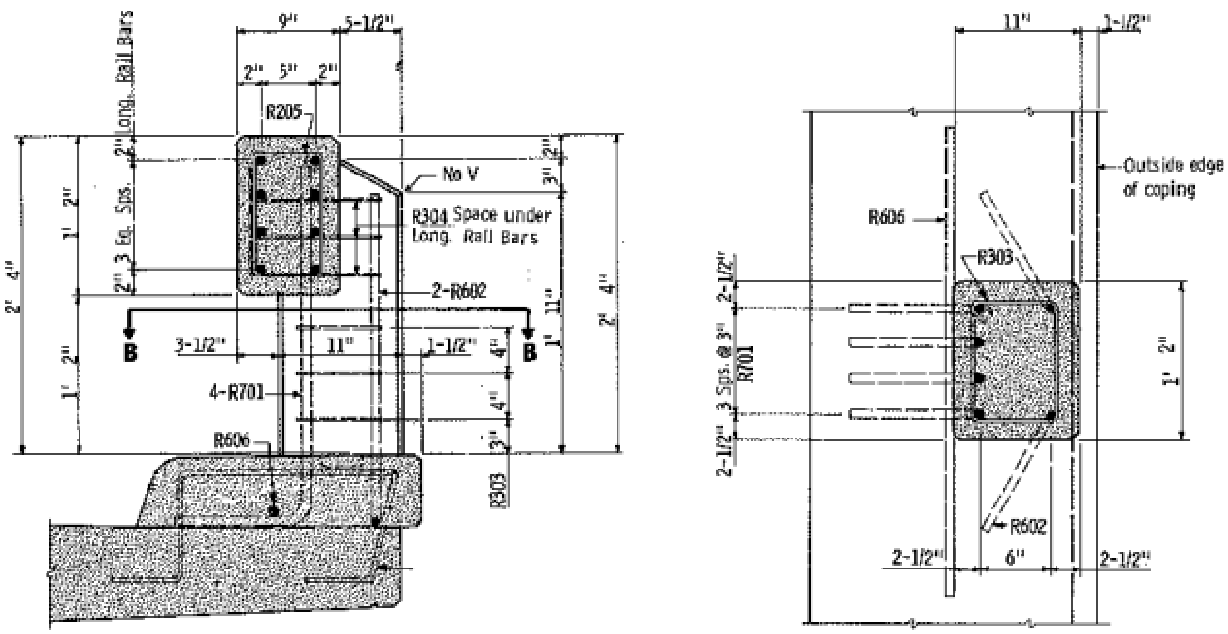


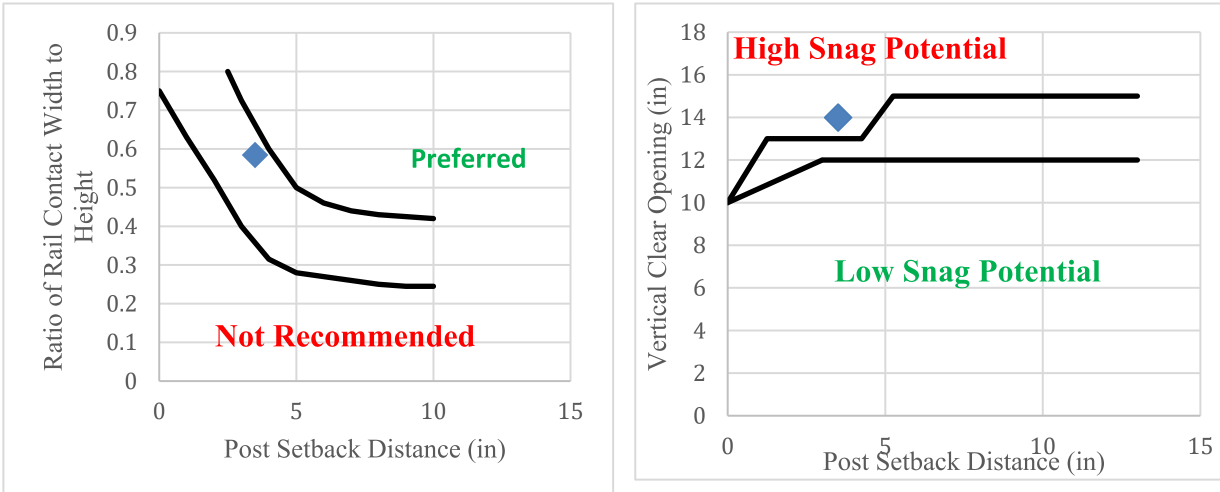
Figure 2-12 Detailed View of One-Line Bridge Rail on Figure 5-397.102.

STABILITY EVALUATION

The One-Line Bridge Rail on Figure 5-397.102 has a height of 34-1/4 inches. The minimum height requirement for a MASH TL-3 bridge rail is 29 inches. Therefore, the One-Line Bridge Rail on Figure 5-397.102 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the One-Line Bridge Rail on Figure 5-397.102. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-13, the geometric data points for the One-Line Bridge Rail on Figure 5-397.102 plot in the marginal region for the Post Setback criteria and in the High Snag Potential region for the Snag Potential criteria. Therefore, the One-Line Bridge Rail on Figure 5-397.102 does not satisfy the geometric evaluation criteria (Not Satisfactory).



(a) Post Setback Criteria (b) Snag Potential

Figure 2-13 Geometric Criteria Assessment of One-Line Bridge Rail on Figure 5-397.102.

STRENGTH EVALUATION

The structural capacity of the One-Line Bridge Rail on Figure 5-397.102 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.22 presents the results from the strength analysis conducted for the One-Line Bridge Rail on Figure 5-397.102. As summarized in Table 2.22, the One-Line Bridge Rail on Figure 5-397.102 does not meet MASH TL-3 structural adequacy criterion due to a lack of strength in the interior section of the barrier, the end section/joint of the barrier, and the separate end post (Not Satisfactory).

Table 2.22 Summary of MASH TL-3 Strength Analysis for One-Line Bridge Rail on Figure 5-397.102.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at an Interior Section	71 kips	53 kips	**Not Satisfactory**
Structural Capacity of the Barrier at an End Section or Joint	71 kips	54 kips	**Not Satisfactory**
Structural Capacity of the End Post	71 kips	69 kips	**Not Satisfactory**

RECOMMENDATION

As summarized in Table 2.23, the One-Line Bridge Rail on Figure 5-397.102 does not satisfy all MASH TL-3 evaluation criteria.

The assessment of occupant risk is considered not satisfactory due to the rail geometrics not plotting in the acceptable regions for the post setback and snag potential criteria (see Figure 2-13). Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Figure 5-397.102 to satisfy MASH occupant risk criteria. The addition of a vertical face to the One-Line Bridge Rail on Figure 5-397.102 would greatly reduce snagging potential and therefore, provide a modification to the rail that would satisfy MASH occupant risk criteria (one possible option).

The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of strength in the interior section of the barrier, the end section/joint of the barrier, and the separate end post (see Table 2.22). Therefore, TTI recommends that modifications be made to the interior section of the barrier, the end section/joint of the barrier, and the separate end post to satisfy MASH TL-3 structural adequacy criterion. Further evaluation and design effort will be required to develop possible options to meet the strength and performance criteria for MASH TL-3 for this design.

Table 2.23 Summary of MASH TL-3 Assessment of One-Line Bridge Rail on Figure 5-397.102.

	Required	**Actual**	**Assessment**
Stability	29 in.	34-1/4 in.	**Satisfactory**
Geometric	See Figure 2-13		**Not Satisfactory**
Strength	See Table 2.22		**Not Satisfactory**

1.1.1.3 One-Line Bridge Rail on Bridge No. 70802 (Appendix C2)

The One-Line Bridge Rail on Bridge No. 70802 is a concrete post and beam system. Appendix C2 contains the details and full analysis for the One-Line Bridge Rail on Bridge No. 70802. Figure 2-14 shows a detailed view of the One-Line Bridge Rail on Bridge No. 70802. Below is a summary of the evaluation results and recommendations.

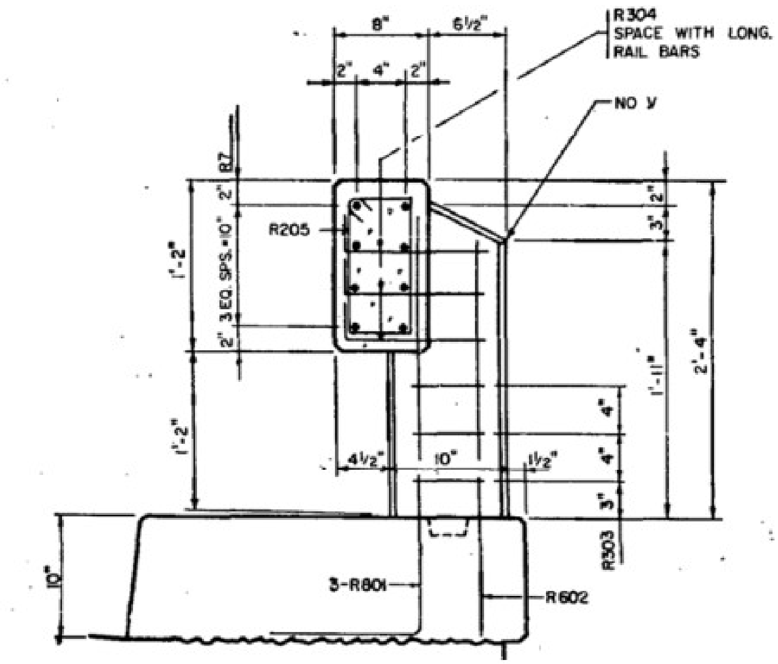


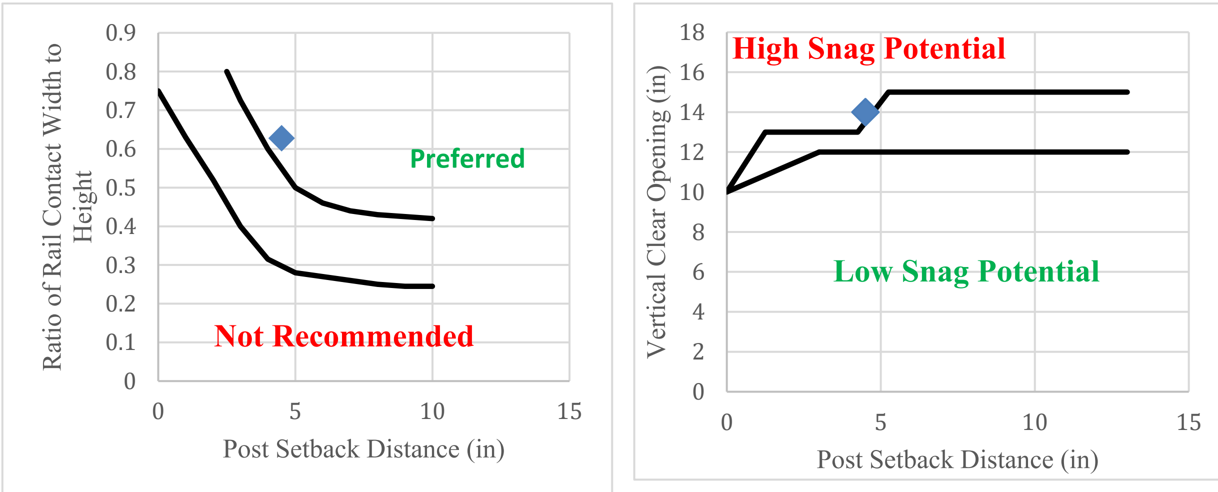
Figure 2-14 Detailed View of One-Line Bridge Rail on Bridge No. 70802.

STABILITY EVALUATION

The One-Line Bridge Rail on Bridge No. 70802 has a height of 38-1/4 inches. The minimum height requirement for a MASH TL-3 bridge rail is 29 inches. Therefore, the One-Line Bridge Rail on Bridge No. 70802 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the One-Line Bridge Rail on Bridge No. 70802. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-15, the geometric data points for the One-Line Bridge Rail on Bridge No. 70802 plot in the Preferred region for the Post Setback criteria and in the High Snag Potential region for the Snag Potential criteria. Therefore, the One-Line Bridge Rail on Bridge No. 70802 does not satisfy the geometric evaluation criteria (Not Satisfactory).



(a) Post Setback Criteria (b) Snag Potential

Figure 2-15 Geometric Criteria Assessment of One-Line Bridge Rail on Bridge No. 70802.

STRENGTH EVALUATION

The structural capacity of the One-Line Bridge Rail on Bridge No. 70802 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (Ft) is 71 kips located at an effective height (He) of 19 inches above the roadway surface. Table 2.24 presents the results from the strength analysis conducted for the One-Line Bridge Rail on Bridge No. 70802. As summarized in Table 2.24, the One-Line Bridge Rail on Bridge No. 70802 does not meet MASH TL-3 structural adequacy criterion due to lack of strength of the interior section and end section/joint of the barrier (Not Satisfactory).

Table 2.24 Summary of MASH TL-3 Strength Analysis for One-Line Bridge Rail on Bridge No. 70802.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at an Interior Section	71 kips	65 kips	**Not Satisfactory**
Structural Capacity of the Barrier at an End Section or Joint	71 kips	54 kips	**Not Satisfactory**

RECOMMENDATION

As summarized in Table 2.25, the One-Line Bridge Rail on Bridge No. 70802 does not satisfy all MASH TL-3 evaluation criteria.

The assessment of occupant risk is considered not satisfactory due to the rail geometrics not plotting in the acceptable region for the snag potential criteria (see Figure 2-15). Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Bridge No. 70802 to satisfy MASH occupant risk criteria. The addition of a vertical face to the One-Line Bridge Rail on Bridge No. 70802 would greatly reduce snagging potential and therefore, provide a modification to the rail that would satisfy MASH occupant risk criteria (one possible option).

The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of strength in the interior section of the barrier and the end section/joint of the barrier (see Table 2.24). Therefore, TTI recommends that modifications be made to the interior section of the barrier and the end section/joint of the barrier to satisfy MASH TL-3 structural adequacy criterion. Further evaluation and design effort will be required to develop possible options to meet the strength and performance criteria for MASH TL-3 for this design.

Table 2.25 Summary of MASH TL-3 Assessment of One-Line Bridge Rail on Bridge No. 70802.

	Required	**Actual**	**Assessment**
Stability	29 in.	38-1/4 in.	**Satisfactory**
Geometric	See Figure 2-15		**Not Satisfactory**
Strength	See Table 2.24		**Not Satisfactory**

2.3.2.2 One-Line Bridge Rail on Bridge No. 21809 (Appendix C3)

The One-Line Bridge Rail on Bridge No. 21809 is a concrete post and beam system. Appendix C3 contains the details and full analysis for the One-Line Bridge Rail on Bridge No. 21809. Figure 2-16 shows a detailed view of the One-Line Bridge Rail on Bridge No. 21809. Below is a summary of the evaluation results and recommendations.

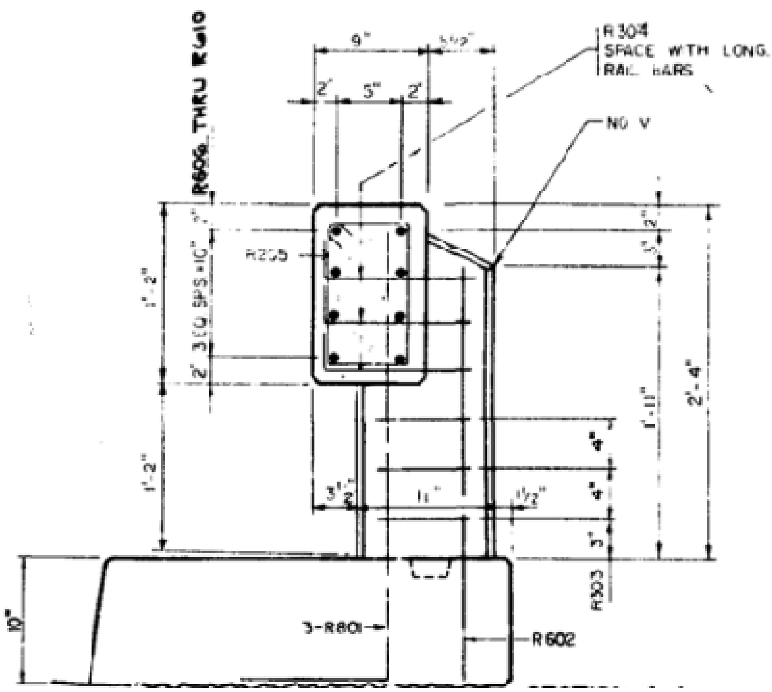


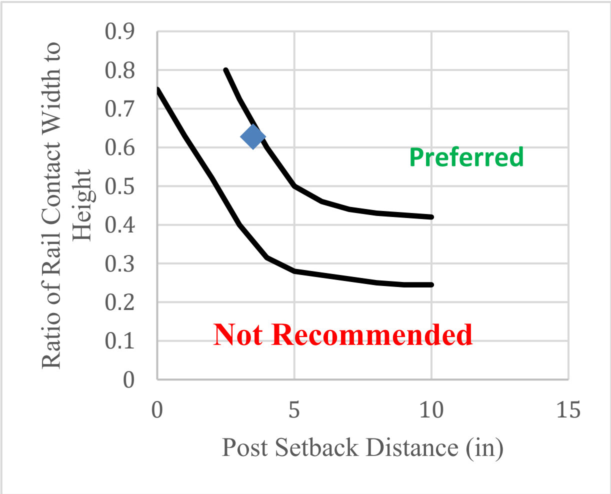
Figure 2-16 Detailed View of One-Line Bridge Rail on Bridge No. 21809.

STABILITY EVALUATION

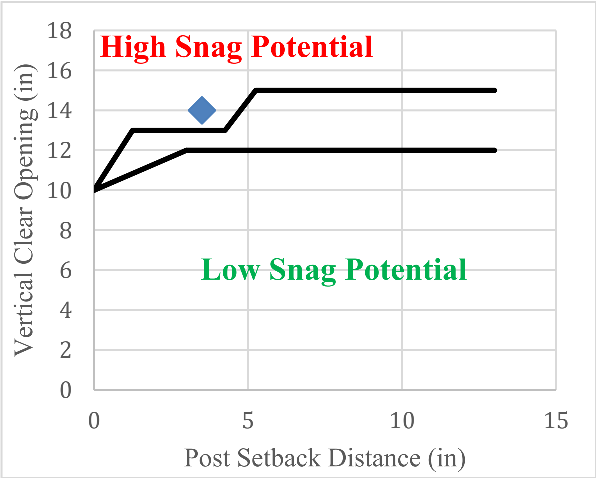
The One-Line Bridge Rail on Bridge No. 21809 has a height of 38-1/4 inches. The minimum height requirement for a MASH TL-3 bridge rail is 29 inches. Therefore, the One-Line Bridge Rail on Bridge No. 21809 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the One-Line Bridge Rail on Bridge No. 21809. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-17, the geometric data points for the One-Line Bridge Rail on Bridge No. 21809 plot in the marginal region for the Post Setback criteria and in the High Snag Potential region for the Snag Potential criteria. Therefore, the One-Line Bridge Rail on Bridge No. 21809 does not satisfy the geometric evaluation criteria (Not Satisfactory).



(a) Post Setback Criteria



(b) Snag Potential

Figure 2-17 Geometric Criteria Assessment of One-Line Bridge Rail on Bridge No. 21809.

STRENGTH EVALUATION

The structural capacity of the One-Line Bridge Rail on Bridge No. 21809 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (Ft) is 71 kips located at an effective height (He) of 19 inches above the roadway surface. Table 2.26 presents the results from the strength analysis conducted for the G barrier on Bridge No. 21809. As summarized in Table 2.26, the One-Line Bridge Rail on Bridge No. 21809 does not meet MASH TL-3 structural adequacy criterion due to lack of strength of the interior section and end section/joint of the barrier (Not Satisfactory).

Table 2.26 Summary of MASH TL-3 Strength Analysis for One-Line Bridge Rail on Bridge No. 21809.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at an Interior Section	71 kips	59 kips	**Not Satisfactory**
Structural Capacity of the Barrier at an End Section or Joint	71 kips	61 kips	**Not Satisfactory**

RECOMMENDATION

As summarized in Table 2.27, the One-Line Bridge Rail on Bridge No. 21809 does not satisfy all MASH TL-3 evaluation criteria.

The assessment of occupant risk is considered not satisfactory due to the rail geometrics not plotting in the acceptable regions for the post setback and snag potential criteria (see Figure 2-17). Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Bridge No. 21809 to satisfy MASH occupant risk criteria. The addition of a vertical face to the One-Line Bridge Rail on Bridge No. 21809 would greatly reduce snagging potential and therefore, provide a modification to the rail that would satisfy MASH occupant risk criteria (one possible option).

The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of strength in the interior section of the barrier and the end section/joint of the barrier (see Table 2.26). Therefore, TTI recommends that modifications be made to the interior section of the barrier and the end section/joint of the barrier to satisfy MASH TL-3 structural adequacy criterion. Further evaluation and design effort will be required to develop possible options to meet the strength and performance criteria for MASH TL-3 for this design.

Table 2.27 Summary of MASH TL-3 Assessment of One-Line Bridge Rail on Bridge No. 21809.

	Required	**Actual**	**Assessment**
Stability	36 in.	38-1/4 in.	**Satisfactory**
Geometric	See Figure 2-17		**Not Satisfactory**
Strength	See Table 2.26		**Not Satisfactory**

2.3.2.3 One-Line Bridge Rail on Bridge No. 69834 (Appendix C4)

The One-Line Bridge Rail on Bridge No. 69834 is a concrete post and beam system. Appendix C4 contains the details and full analysis for the One-Line Bridge Rail on Bridge No. 69834. Figure 2-18 shows a detailed view of the One-Line Bridge Rail on Bridge No. 69834. Below is a summary of the evaluation results and recommendations.

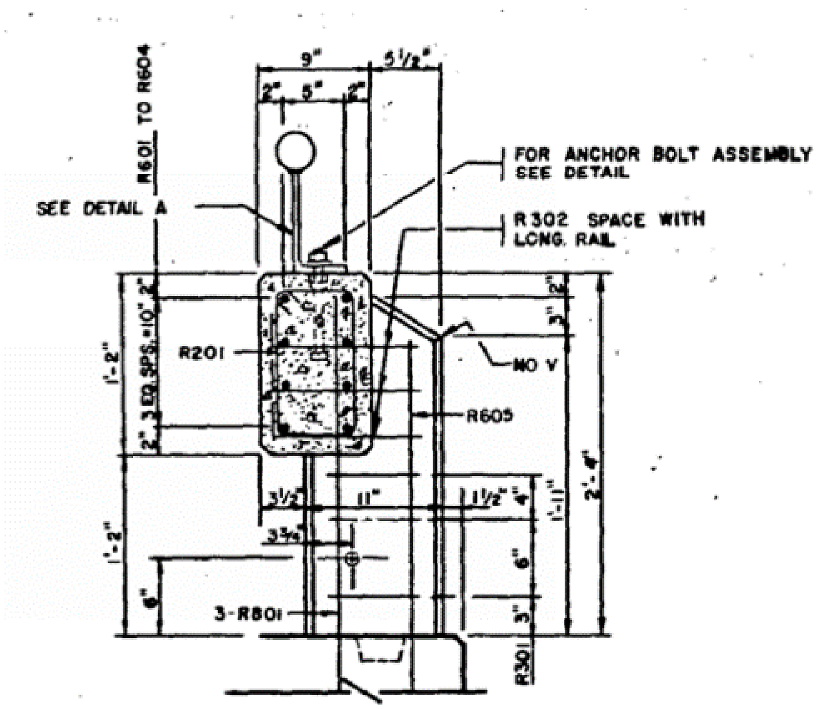


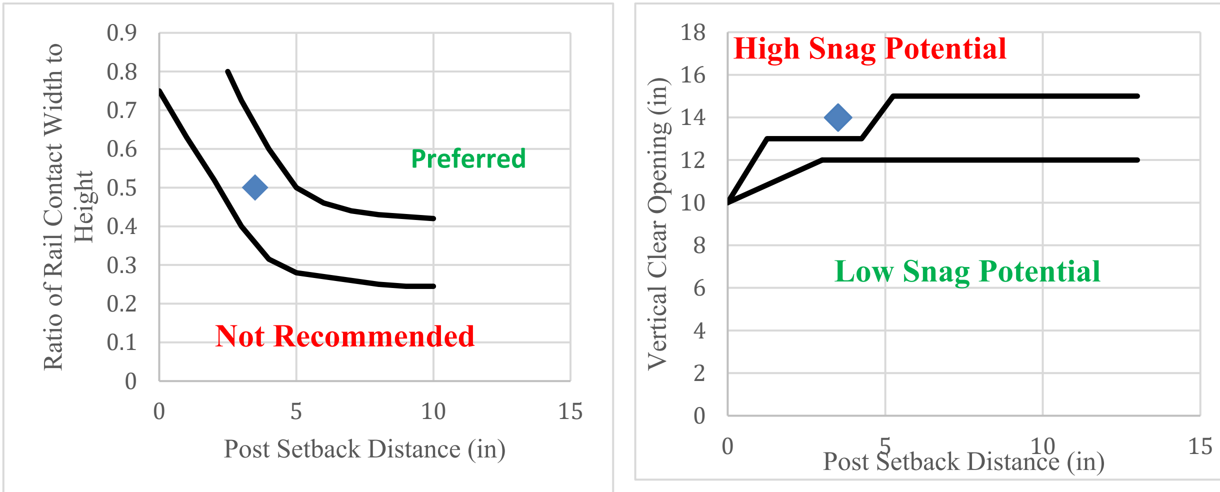
Figure 2-18 Detailed View of One-Line Bridge Rail on Bridge No. 69834.

STABILITY EVALUATION

The One-Line Bridge Rail on Bridge No. 69834 has a height of 28 inches. The minimum height requirement for a MASH TL-3 bridge rail is 29 inches. Therefore, the One-Line Bridge Rail on Bridge No. 69834 does not meet the MASH TL-3 minimum height stability criterion (Not Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the One-Line Bridge Rail on Bridge No. 69834. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-19, the geometric data points for the One-Line Bridge Rail on Bridge No. 69834 plot in the marginal region for the Post Setback criteria and in the High Snag Potential region for the Snag Potential criteria. Therefore, the One-Line Bridge Rail on Bridge No. 69834 does not satisfy the geometric evaluation criteria (Not Satisfactory).



(a) Post Setback Criteria

(b) Snag Potential

Figure 2-19 Geometric Criteria Assessment of One-Line Bridge Rail on Bridge No. 69834.

STRENGTH EVALUATION

The structural capacity of the One-Line Bridge Rail on Bridge No. 69834 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.28 presents the results from the strength analysis conducted for the One-Line Bridge Rail on Bridge No. 69834. As summarized in Table 2.28, the One-Line Bridge Rail on Bridge No. 69834 does not meet MASH TL-3 structural adequacy criterion due to a lack of strength in the interior section and end section/joint of the barrier (Not Satisfactory).

Table 2.28 Summary of MASH TL-3 Strength Analysis for One-Line Bridge Rail on Bridge No. 69834.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at an Interior Section	71 kips	41 kips	**Not Satisfactory**
Structural Capacity of the Barrier at an End Section or Joint	71 kips	41 kips	**Not Satisfactory**

RECOMMENDATION

As summarized in Table 2.29, the One-Line Bridge Rail on Bridge No. 69834 does not satisfy all MASH TL-3 evaluation criteria.

The assessment of the minimum height stability criterion is considered not satisfactory due to the rail not meeting the minimum height requirement for a MASH TL-3 bridge rail. Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Bridge No. 69834 to satisfy the MASH TL-3 minimum height stability criterion.

The assessment of occupant risk is considered not satisfactory due to the rail geometrics not plotting in the acceptable regions for the post setback and snag potential criteria (see Figure 2-19). Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Bridge No. 69834 to satisfy MASH occupant risk criteria. The addition of a vertical face to the One-Line Bridge Rail on Bridge No. 69834 would greatly reduce snagging potential and therefore, provide a modification to the rail that would satisfy MASH occupant risk criteria (one possible option).

The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of strength in the interior section and end section/joint of the barrier (see Table 2.28). Therefore, TTI recommends that modifications be made to the interior section and end section/joint of the barrier to satisfy MASH TL-3 structural adequacy criterion. Further evaluation and design effort will be required to develop possible options to meet the strength and performance criteria for MASH TL-3 for this design.

Table 2.29 Summary of MASH TL-3 Assessment of One-Line Bridge Rail on Bridge No. 69834.

	Required	**Actual**	**Assessment**
Stability	29 in.	28 in.	**Not Satisfactory**
Geometric	See Figure 2-19		**Not Satisfactory**
Strength	See Table 2.28		**Not Satisfactory**

1.1.1.4 One-Line Bridge Rail on Figure 5-397.104 (Appendix C5)

The One-Line Bridge Rail on Figure 5-397.104 is a concrete post and beam system with an 18-inch long separate concrete end post. Appendix C5 contains the details and full analysis for the One-Line Bridge Rail on Figure 5-397.104. Figure 2-20 shows a detailed view of the One-Line Bridge Rail on Figure 5-397.104. Below is a summary of the evaluation results and recommendations.

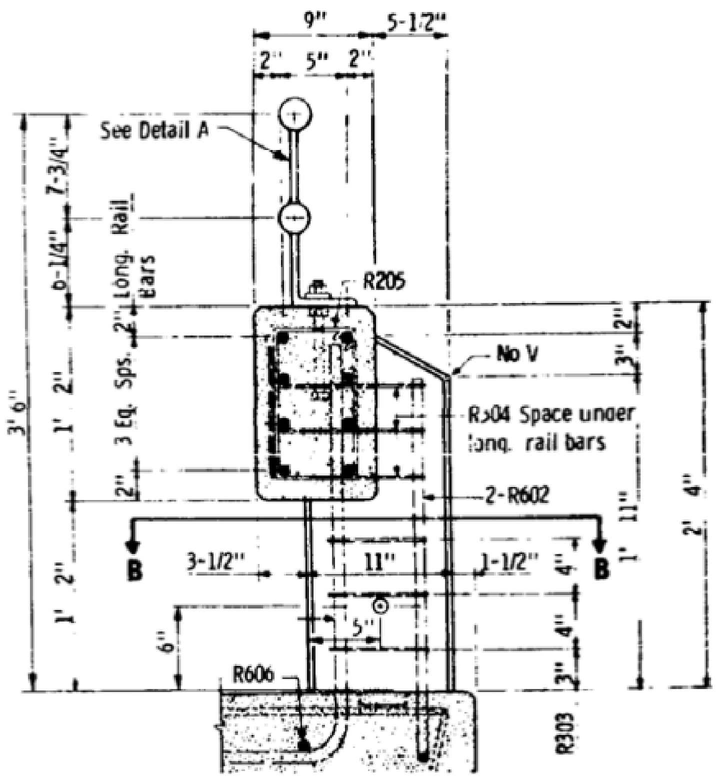


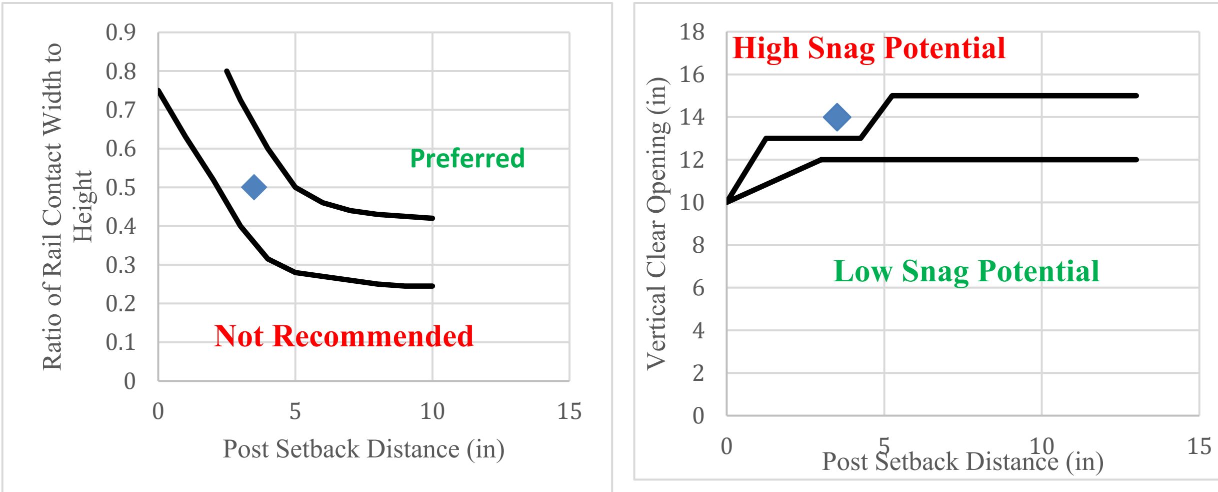
Figure 2-20 Detailed View of One-Line Bridge Rail on Figure 5-397.104.

STABILITY EVALUATION

The One-Line Bridge Rail on Figure 5-397.104 has a height of 28 inches. The minimum height requirement for a MASH TL-3 bridge rail is 29 inches. Therefore, the One-Line Bridge Rail on Figure 5-397.104 does not meet the MASH TL-3 minimum height stability criterion (Not Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the One-Line Bridge Rail on Figure 5-397.104. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-21, the geometric data points for the One-Line Bridge Rail on Figure 5-397.104 plot in the marginal region for the Post Setback criteria and in the High Snag Potential region for the Snag Potential criteria. Therefore, the One-Line Bridge Rail on Figure 5-397.104 does not satisfy the geometric evaluation criteria (Not Satisfactory).



(a) Post Setback Criteria

(b) Snag Potential

Figure 2-21 Geometric Criteria Assessment of One-Line Bridge Rail on Figure 5-397.104.

STRENGTH EVALUATION

The structural capacity of the One-Line Bridge Rail on Figure 5-397.104 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.30 presents the results from the strength analysis conducted for the One-Line Bridge Rail on Figure 5-397.104. As summarized in Table 2.30, the One-Line Bridge Rail on Figure 5-397.104 does not meet MASH TL-3 structural adequacy criterion due to a lack of strength in the interior section of the barrier, the end section/joint of the barrier, and the separate end post (Not Satisfactory).

Table 2.30 Summary of MASH TL-3 Strength Analysis for One-Line Bridge Rail on Figure 5-397.104.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at an Interior Section	71 kips	40 kips	**Not Satisfactory**
Structural Capacity of the Barrier at an End Section or Joint	71 kips	42 kips	**Not Satisfactory**
Structural Capacity of the End Post	71 kips	69 kips	**Not Satisfactory**

RECOMMENDATION

As summarized in Table 2.31, the One-Line Bridge Rail on Figure 5-397.104 does not satisfy all MASH TL-3 evaluation criteria.

The assessment of the minimum height stability criterion is considered not satisfactory due to the rail not meeting the minimum height requirement for a MASH TL-3 bridge rail. Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Figure 5-397.104 to satisfy the MASH TL-3 minimum height stability criterion.

The assessment of occupant risk is considered not satisfactory due to the rail geometrics not plotting in the acceptable regions for the post setback and snag potential criteria (see Figure 2-21). Therefore, TTI recommends that modifications be made to the One-Line Bridge Rail on Figure 5-397.104 to satisfy MASH occupant risk criteria. The addition of a vertical face to the One-Line Bridge Rail on Figure 5-397.104 would greatly reduce snagging potential and therefore, provide a modification to the rail that would satisfy MASH occupant risk criteria (one possible option).

The MASH TL-3 structural adequacy criterion is not satisfied due to a lack of strength in the interior section of the barrier, the end section/joint of the barrier, and the separate end post (see Table 2.30). Therefore, TTI recommends that modifications be made to the interior section of the barrier, the end section/joint of the barrier, and the separate end post to satisfy MASH TL-3 structural adequacy criterion. Further evaluation and design effort will be required to develop possible options to meet the strength and performance criteria for MASH TL-3 for this design.

Table 2.31 Summary of MASH TL-3 Assessment of One-Line Bridge Rail on Figure 5-397.104.

	Required	Actual	Assessment
Stability	29 in.	28 in.	**Not Satisfactory**
Geometric	See Figure 2-21		**Not Satisfactory**
Strength	See Table 2.30		**Not Satisfactory**

2.3.3 G Barriers

2.3.3.1 G Barrier on Bridge No. 09830 (Figure 5-397.107) (Appendix D1)

The G barrier on Bridge No. 09830 (Figure 5-397.107) is a metal post and beam system mounted on top of a 28-inch high Jersey Shape. This barrier has a separate end post that is 19-5/8 inches long. Appendix D1 contains the details and full analysis for the G barrier on Bridge No. 09830. Figure 2-22 shows a detailed view of the G barrier on Bridge No. 09830. Below is a summary of the evaluation results and recommendations.

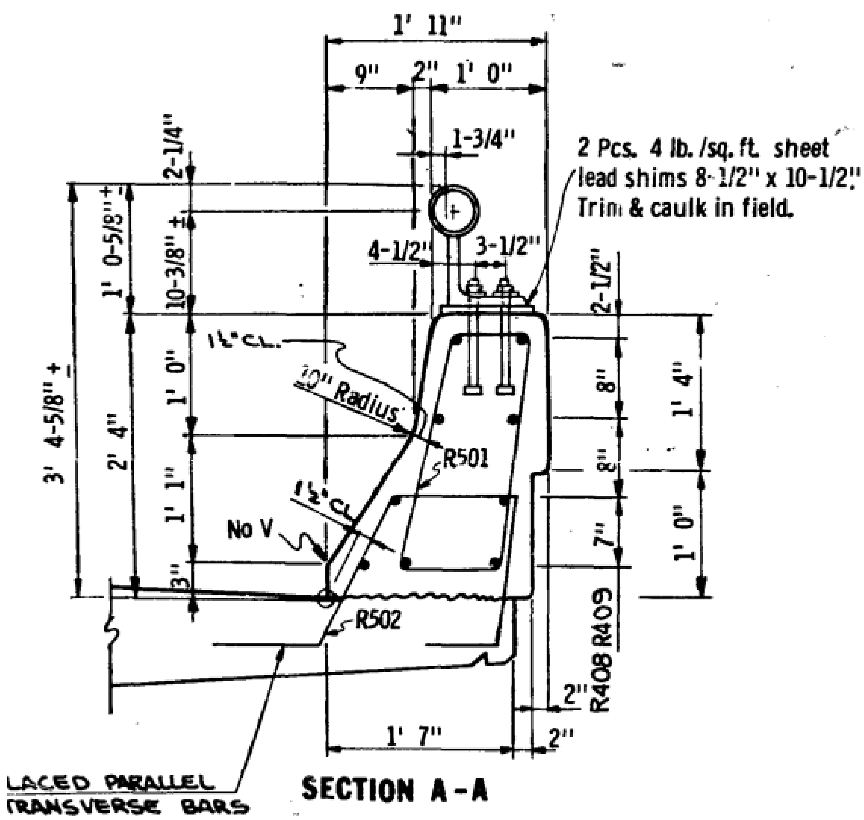


Figure 2-22 Detailed View of G Barrier on Bridge No. 09830.

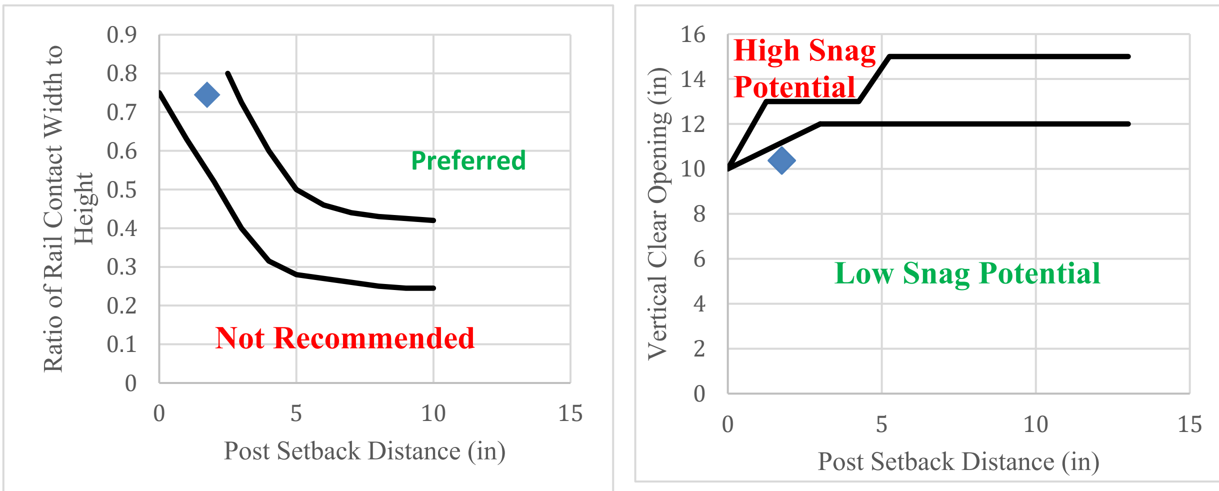
STABILITY EVALUATION

The G barrier on Bridge No. 09830 has a height of 40-5/8 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the G barrier on Bridge No. 09830 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the G barrier on Bridge No. 09830. The appropriate data points were plotted against the current

AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-23, the barriers' geometric data points plot in the marginal region for the Post Setback criteria and in the acceptable region for the Snag Potential criteria. Therefore, the G barrier on Bridge No. 09830 does not satisfy the geometric evaluation criteria (Marginal).



(a) Post Setback Criteria

(b) Snag Potential

Figure 2-23 Geometric Criteria Assessment of G Barrier on Bridge No. 09830.

STRENGTH EVALUATION

The structural capacity of the G barrier on Bridge No. 09830 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.32 presents the results from the strength analysis conducted for the G barrier on Bridge No. 09830. As summarized in Table 2.32, the G barrier on Bridge No. 09830 meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.32 Summary of MASH TL-3 Strength Analysis for G Barrier on Bridge No. 09830.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	190 kips	**Satisfactory**
Structural Capacity of the Barrier at a Post	71 kips	186 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	119 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.33, the G barrier on Bridge No. 09830 does not satisfy all MASH TL-3 evaluation criteria. The assessment of occupant risk is not considered satisfactory due to the barrier geometrics plotting in the marginal region for the post setback criteria (see Figure 2-23). Therefore, TTI recommends that modifications be made to the G barrier on Bridge No. 09830 to satisfy the MASH geometric evaluation criteria.

Table 2.33 Summary of MASH TL-3 Assessment of G Barrier on Bridge No. 09830.

	Required	Actual	Assessment
Stability	29 in.	40-5/8 in.	**Satisfactory**
Geometric	See Figure 2-23		**Marginal**
Strength	See Table 2.32		**Satisfactory**

2.3.3.2 G Barrier on Bridge No. 19021 (Figure 5-397.109) (Appendix D2)

The G barrier on Bridge No. 19021 (Figure 5-397.109) is a metal post and beam system mounted on top of a 28-inch high Jersey Shape. Appendix D2 contains the details and full analysis for the G barrier on Bridge No. 19021. Figure 2-24 shows a detailed view of the G barrier on Bridge No. 19021. Below is a summary of the evaluation results and recommendations.

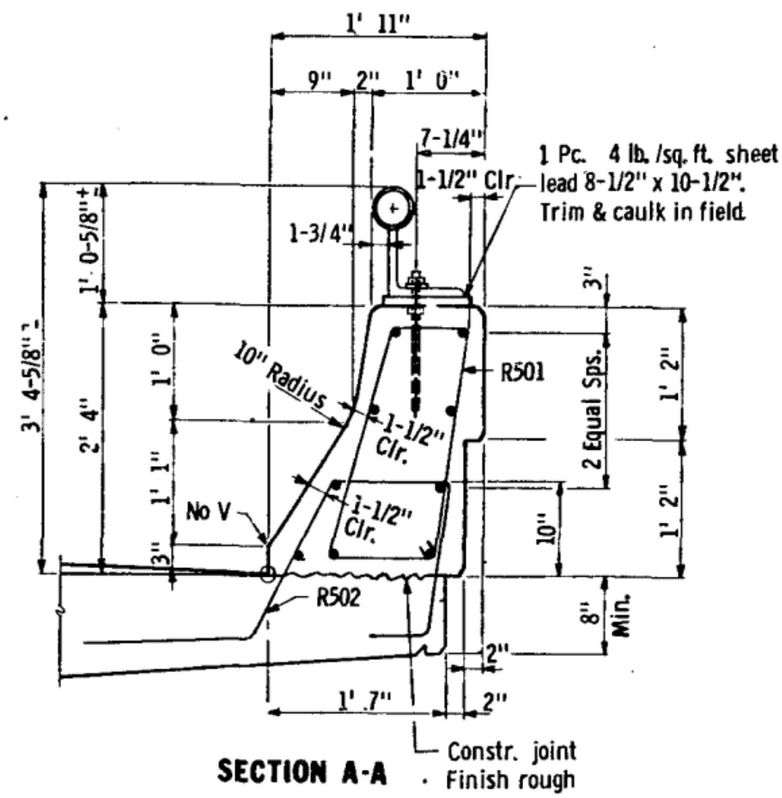


Figure 2-24 Detailed View of G Barrier on Bridge No. 19021.

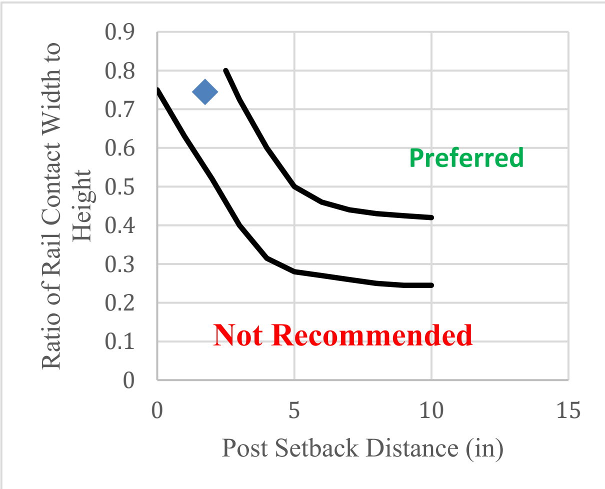
STABILITY EVALUATION

The G barrier on Bridge No. 19021 has a height of 40-5/8 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the G barrier on Bridge No. 19021 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

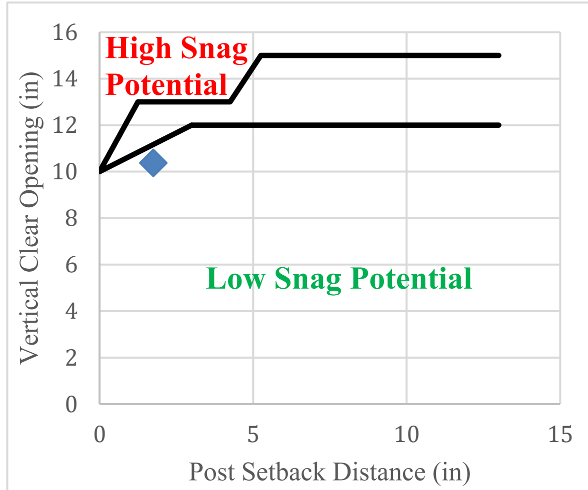
GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the G barrier on Bridge No. 19021. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-25, the barriers' geometric data points plot in the marginal region for the Post Setback criteria and in the acceptable region for the Snag

Potential criteria. Therefore, the G barrier on Bridge No. 19021 does not satisfy the geometric evaluation criteria (Marginal).



(a) Post Setback Criteria



(b) Snag Potential

Figure 2-25 Geometric Criteria Assessment of G Barrier on Bridge No. 19021.

STRENGTH EVALUATION

The structural capacity of the G barrier on Bridge No. 19021 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.34 presents the results from the strength analysis conducted for the G barrier on Bridge No. 19021. As summarized in Table 2.34, the G barrier on Bridge No. 19021 meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.34 Summary of MASH TL-3 Strength Analysis for G Barrier on Bridge No. 19021.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	218 kips	**Satisfactory**
Structural Capacity of the Barrier at a Post	71 kips	214 kips	**Satisfactory**
Structural Capacity of the End Post and the Conjoining Barrier Segment	71 kips	238 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.35, the G barrier on Bridge No. 19021 does not satisfy all MASH TL-3 evaluation criteria. The assessment of occupant risk is not considered satisfactory due to the barrier geometrics plotting in the marginal region for the post setback criteria (see Figure 2-25). Therefore, TTI recommends that modifications be made to the G barrier on Bridge No. 19021 to satisfy the MASH geometric evaluation criteria.

Table 2.35 Summary of MASH TL-3 Assessment of G Barrier on Bridge No. 19021.

	Required	Actual	Assessment
Stability	29 in.	40-5/8 in.	**Satisfactory**
Geometric	See Figure 2-25		**Marginal**
Strength	See Table 2.34		**Satisfactory**

2.3.3.3 G Barrier on Bridge No. 86812 (Figure 5-397.107) (Appendix D3)

The G barrier on Bridge No. 86812 (Figure 5-397.107) is a metal post and beam system mounted on top of a 28-inch high Jersey Shape, with a separate end post that is 18 inches long. Appendix D3 contains the details and full analysis for the G barrier on Bridge No. 86812. Figure 2-26 shows a detailed view of the G barrier on Bridge No. 86812. Below is a summary of the evaluation results and recommendations.

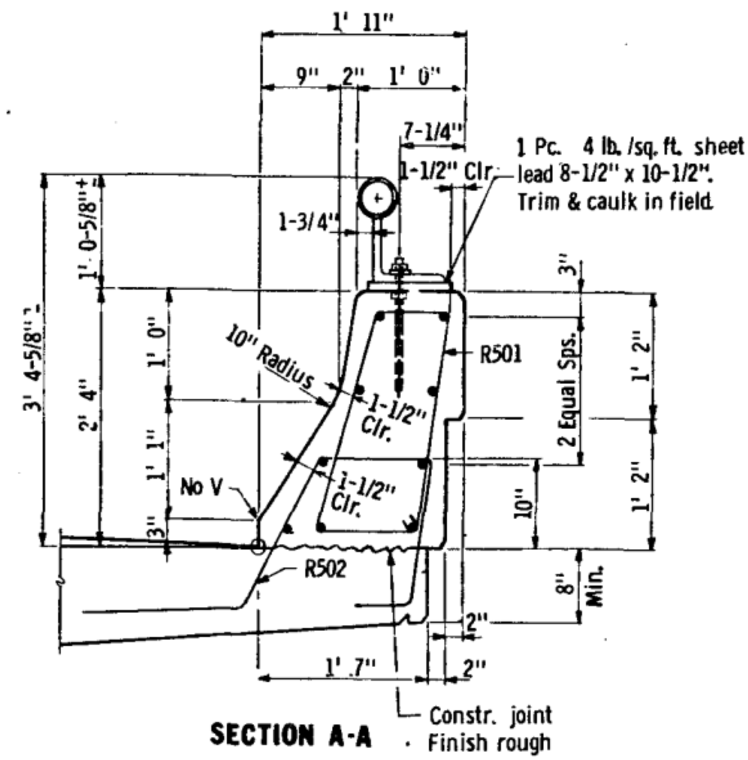


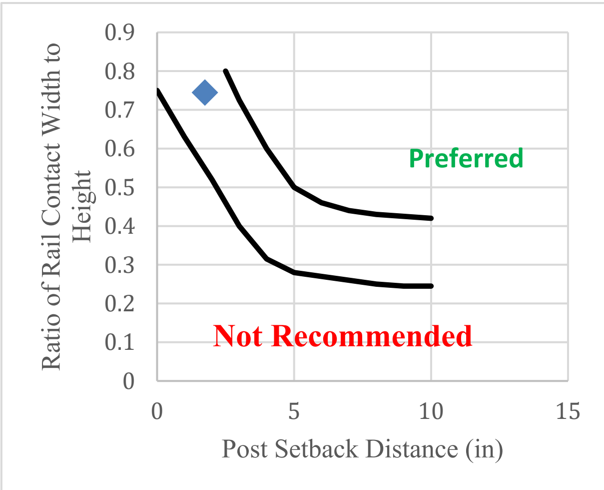
Figure 2-26 Detailed View of G Barrier on Bridge No. 86812.

STABILITY EVALUATION

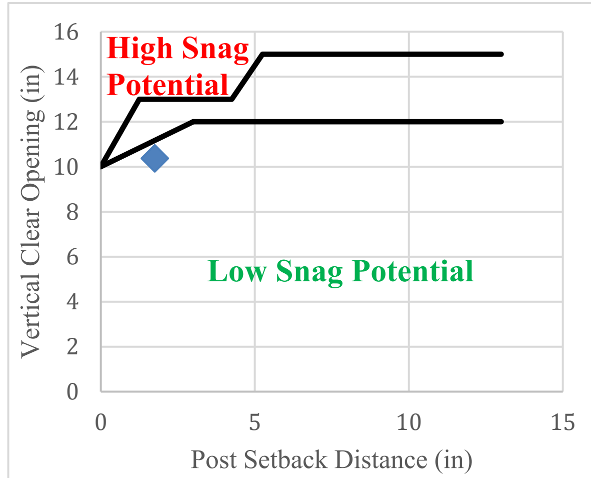
The G barrier on Bridge No. 86812 has a height of 40-5/8 inches. The minimum height requirement for a MASH TL-3 bridge barrier is 29 inches. Therefore, the G barrier on Bridge No. 86812 meets the MASH TL-3 minimum height stability criterion (Satisfactory).

GEOMETRIC EVALUATION

Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the G barrier on Bridge No. 86812. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 2-27, the barriers' geometric data points plot in the marginal region for the Post Setback criteria and in the acceptable region for the Snag Potential criteria. Therefore, the G barrier on Bridge No. 86812 does not satisfy the geometric evaluation criteria (Marginal).



(a) Post Setback Criteria



(b) Snag Potential

Figure 2-27 Geometric Criteria Assessment of G Barrier on Bridge No. 86812.

STRENGTH EVALUATION

The structural capacity of the G barrier on Bridge No. 86812 was compared to the current recommended MASH TL-3 transverse design impact load. The MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface. Table 2.36 presents the results from the strength analysis conducted for the G barrier on Bridge No. 86812. As summarized in Table 2.36, the G barrier on Bridge No. 86812 meets MASH TL-3 structural adequacy criterion (Satisfactory).

Table 2.36 Summary of MASH TL-3 Strength Analysis for G Barrier on Bridge No. 86812.

Strength Check	Required	Actual	Assessment
Structural Capacity of the Barrier at Midspan	71 kips	218 kips	**Satisfactory**
Structural Capacity of the Barrier at a Post	71 kips	214 kips	**Satisfactory**
Structural Capacity of the End Post	71 kips	88 kips	**Satisfactory**

RECOMMENDATION

As summarized in Table 2.37, the G barrier on Bridge No. 86812 does not satisfy all MASH TL-3 evaluation criteria. The assessment of occupant risk is not considered satisfactory due to the barrier geometrics plotting in the marginal region for the post setback criteria (see Figure 2-27). Therefore, TTI recommends that modifications be made to the G barrier on Bridge No. 86812 to satisfy the MASH geometric evaluation criteria.

Table 2.37 Summary of MASH TL-3 Assessment of G Barrier on Bridge No. 86812.

	Required	Actual	Assessment
Stability	29 in.	40-5/8 in.	**Satisfactory**
Geometric	See Figure 2-27		**Marginal**
Strength	See Table 2.36		**Satisfactory**

CHAPTER 3: BARRIER RETROFIT METHODOLOGY AND GUIDANCE

3.1 END POST RETROFIT WITH DRILLED SHAFT

3.1.1 Design of Separate End Post Grade Beam with a Single Shaft

Based on the analyses results performed for Task 2, there are numerous design cases that were considered unsatisfactory with respect to MASH TL-3 requirements due to the structural deficiency of the separate end posts. As part of Task 3 under this project, TTI has designed a new end post that could be used for all "J" and "F" Shape barriers. The new end post design presented herein meets the strength and performance requirements of MASH TL-3. The soil properties used for this design included a loose sand with a friction angle (φ) of 25 degrees and a dry unit weight of 110 lbs. per cubic foot. For a 1-degree reduction in soil friction angle, the depth of the post should increase by 4 inches. The new end post is supported by a 24-inch diameter by 8 feet long drilled shaft. The minimum length and minimum top thickness of the new end post are 48 and 12 inches, respectively. Vertical reinforcement in the end post shall consist of #5 bars at 6 inches (max.) on center. The new end post is supported by a 30-inch square grade beam cast on top of the 24-inch diameter drilled shaft. Longitudinal reinforcement in the grade beam consists of five (5) #6 bars equally spaced on each face with 5 additional #6 bars located on the top and bottom sides (15 total longitudinal bars). These bars shall be placed within the #5 stirrups. Vertical reinforcement in the grade beam consists of #5 enclosed stirrups spaced on 6-inch centers. Reinforcement in the 24-inch diameter drill shaft consists of 12 vertical #6 bars enclosed within #4 stirrups. All reinforcing steel is Grade 60. All concrete shall have a minimum compressive strength of 4000 psi. Please refer to Figure 3-1 through Figure 3-5 for additional information. A curb is not shown on these details. It is at the discretion of MnDOT, and the MASH 2016 crashworthy details currently in use by MnDOT, whether or not to use a curb. The analysis calculations for this End Post Retrofit with drilled shaft design are shown in Appendix E1.

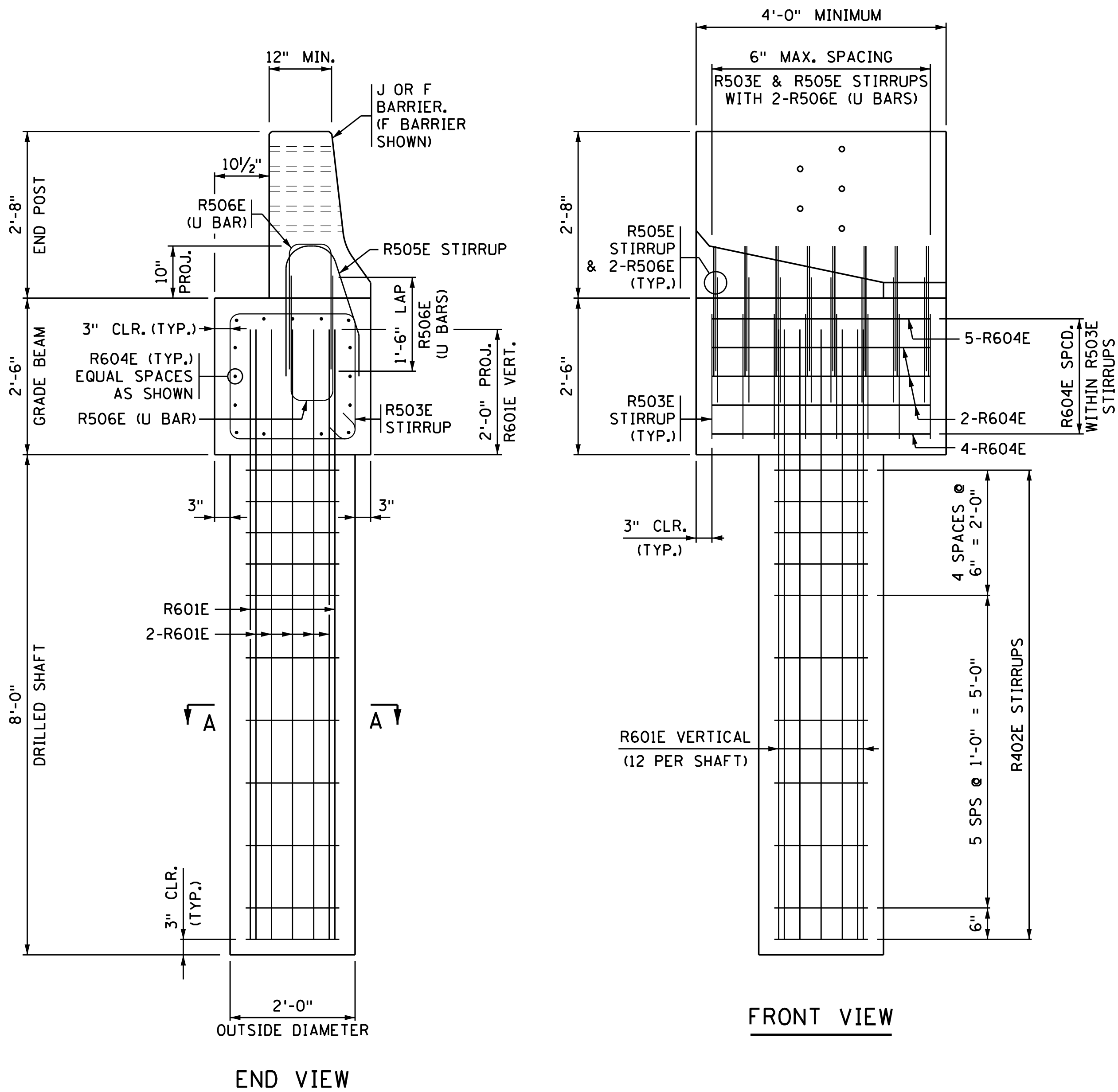


Figure 3-1 Detailed Views of End Post Retrofit with Drilled Shaft.

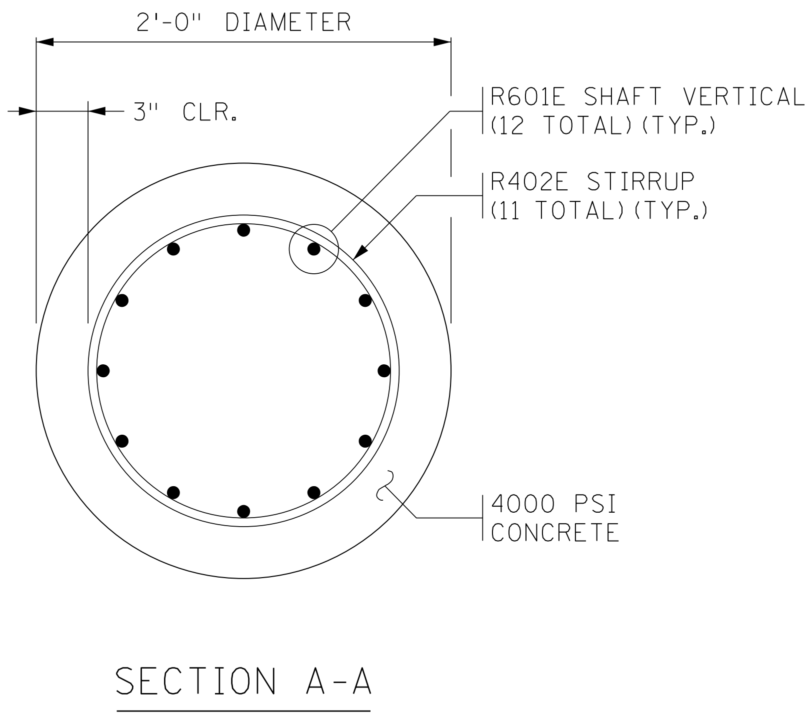


Figure 3-2 Section View of End Post Retrofit with Drilled Shaft.

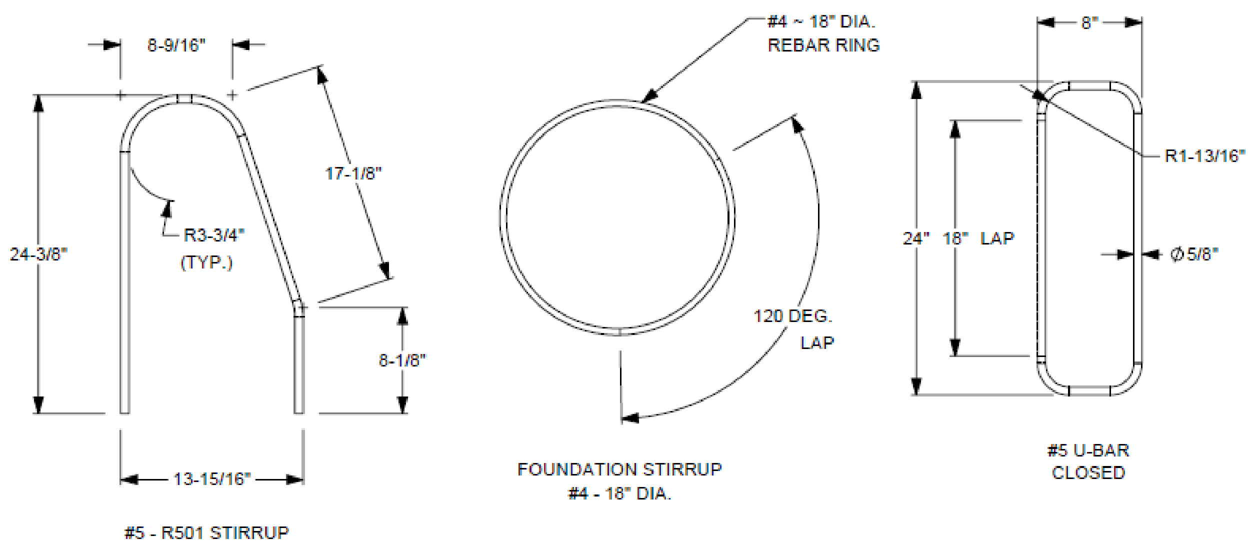


Figure 3-3 Rebar Details for End Post Retrofit with Drilled Shaft.

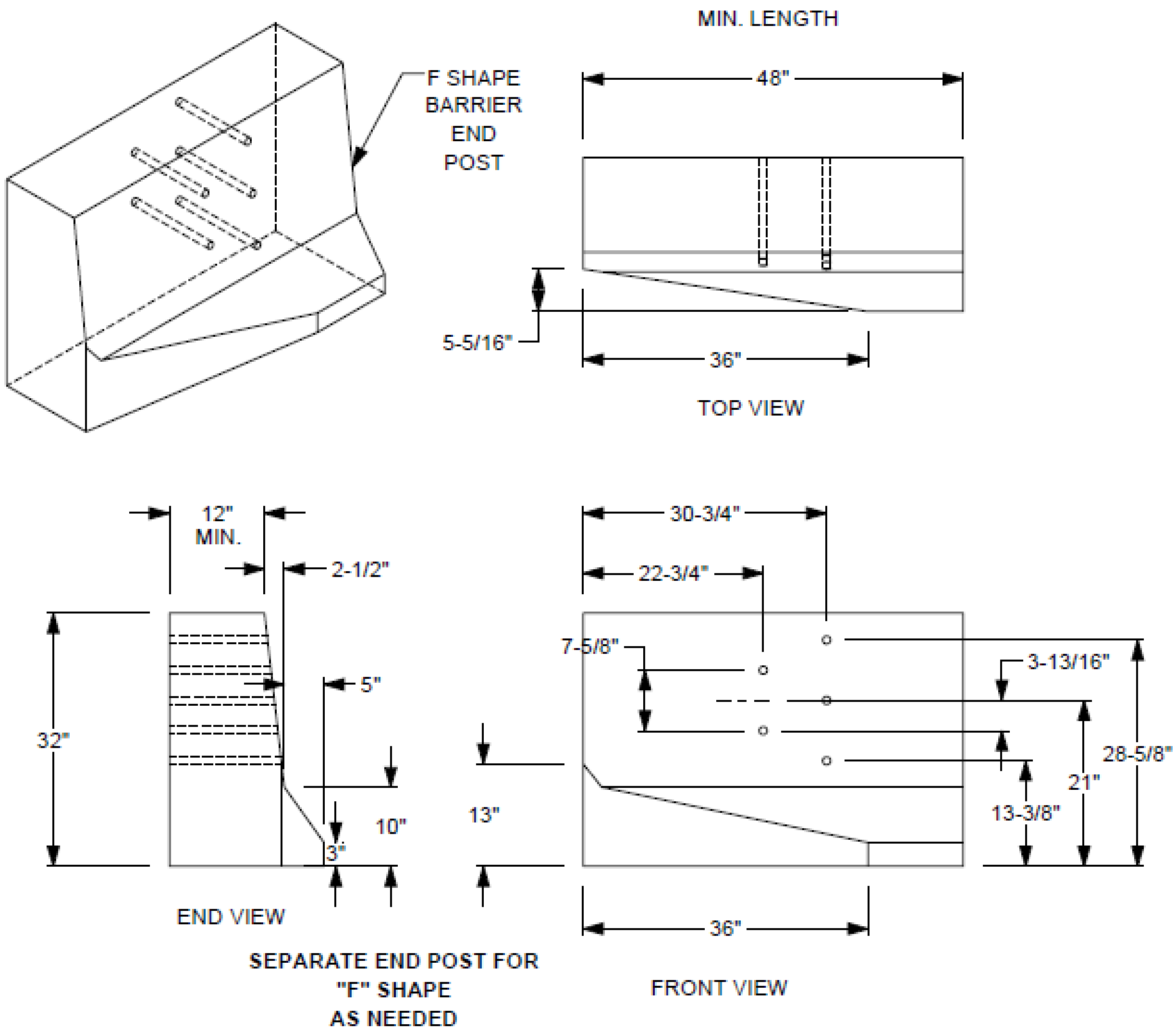


Figure 3-4 Additional Detailed Views of End Post (F Shape) Retrofit with Drilled Shaft.

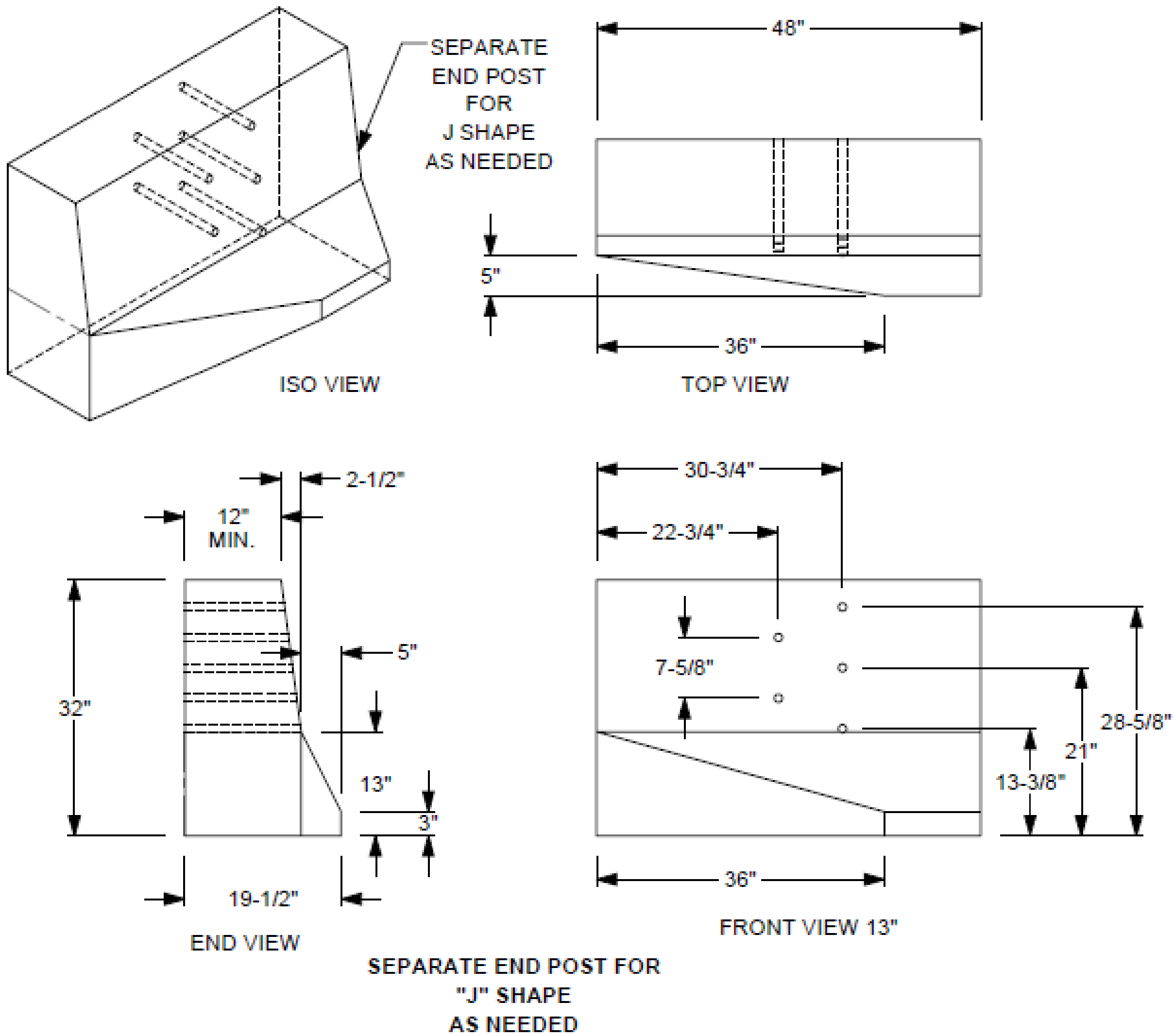


Figure 3-5 Additional Detailed Views of End Post (J Shape) Retrofit with Drilled Shaft.

For the new separate end posts for “G” shape barriers, it is recommended that information provided in Midwest Roadside Safety Facility Research Project No. TPF-5(193) Supplement #103 (ref. 8) and MwRSF Transportation Research Board (TRB) Paper 18-05386 (ref. 9) be used to develop the separate “G” Shape Transition Section. TTI recommends the transition separate end post be designed with a vertical face connection for the Thrie Beam end shoe to optimize vehicle stability during impact. However, the adjacent bridge barrier section nearest to the bridge end shall not be a vertical section shape. Thus, the downstream end of the separate end post transition section must contain a G-Shape aligned with the adjacent concrete G-Shape Barrier section on the bridge. Shape transitions shall be gradual to prevent vehicle instabilities. Based on the information provided by MwRSF, transitions to the face geometry shall incorporate a maximum 10:1 lateral slope to transition the “G” Shape to the MwRSF standardized buttress (ref. 8,9). Shape transitioning may begin 6 inches downstream of the thrie beam terminal connector or 8 inches downstream of the attachment bolts. For drastic shape changes, the length of the buttress may need to be extended beyond its 7 ft minimum length. Figure 3-6 shows a detail of the shape transition from the PennDOT 42 inches F-shape barrier to the MwRSF standardized buttress. Figure 3-7 shows detailed views of an end post retrofit with drilled shafts for the "G" shape barriers.

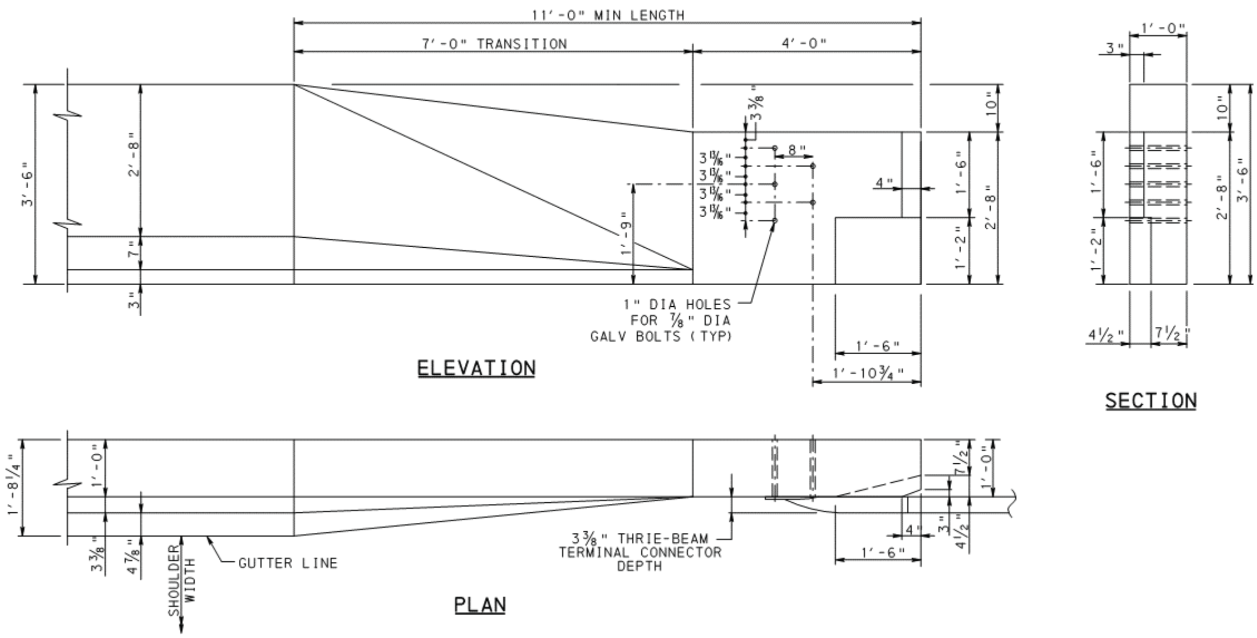


Figure 3-6 F-Shape (42 inches) Concrete Bridge Barrier Transition

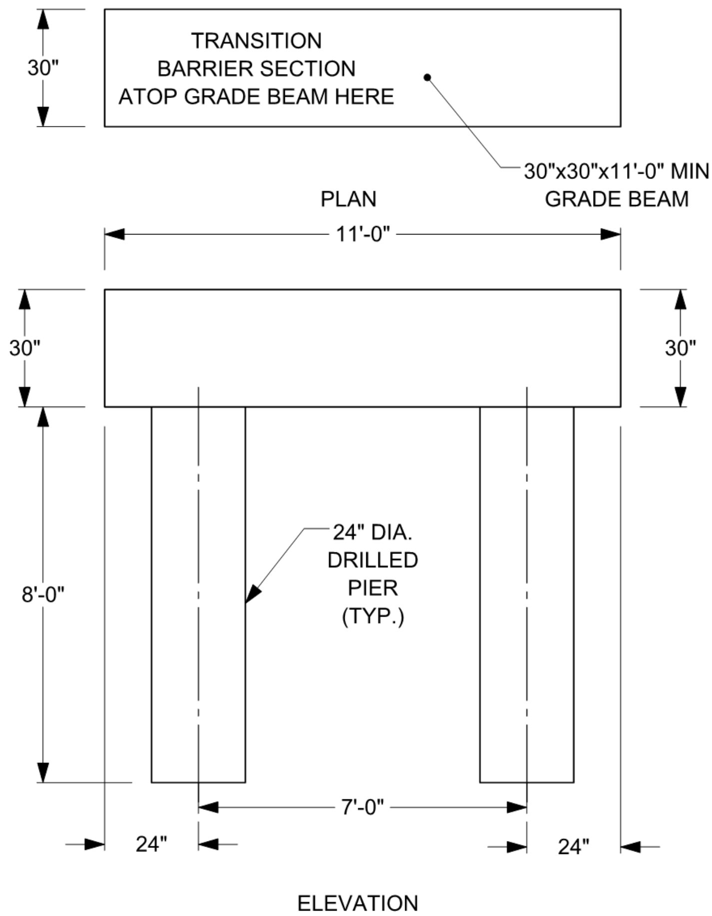


Figure 3-7 Detailed Views of End Post Retrofit with Drilled Shafts for "G" Shape Barriers

Height transitions may be necessary for attachment to taller bridge barriers. The upstream end of the MwRSF buttress was successfully tested with a vertical taper of 4 inches over 24 inches in length. This vertical slope on the upstream may be continued upward with the same 6:1 slope until the desired height is reach. If the adjacent bridge barrier is only 32 inches in height, the entire buttress can be installed with a constant 32-inch top height.

Based on the required length of the "G" Shape separate end transition needed for this project, it is recommended that two drilled piers similar to those used for the "J" and "F" shape barriers be used. The same beam details as used for the "J" and "F" barriers (only longer) are also recommended for the "G" Shape separate end post/transition as recommended herein.

3.1.2 Minimum Taper Design

Figure 3-4 and Figure 3-5 shows the recommended taper shapes at the toe of the barrier at the transition connection end for the J and F barriers. Please refer to the information provided in the

MwRSF Report and TRB Paper (ref. 8, 9) for additional information for the minimum tapers for the G barrier.

3.1.3 Design of the Shape on Top of the Grade Beam

Based on the details shown in Figure 3-1, a 30” x 30” x 4’-0” long grade beam anchored to the top of a 24-inch diameter drilled shaft is recommended to support the end wall post for the J and F barriers. A longer grade beam supported by two drilled shafts is recommended for the G barrier transition. Please refer to the referenced MwRSF Report and TRB Paper for the minimum length of grade beam necessary for the G barrier. All reinforcing steel shall be Grade 60 and all concrete shall have a minimum compressive strength of 4000 psi. Please refer to Figure 3-1 through Figure 3-5 for additional information.

3.1.4 Bolt Thrie Beam Directly to End Post on Face without Steel Wedge Plate

TTI recently performed MASH Test 3-21 on a TxDOT Single Slope Barrier with the 10-Gage Thrie Beam End Shoe bolted directly to the sloped face of the TXDOT SSTR Single Slope Barrier (without wedge plate). The results of this crash test were successful with respect to MASH Test 3-21. A section view of the TxDOT Thrie-Beam transition to Single Slope Barrier is provided in Figure 3-8.

Based on the successful performance of the TxDOT Thrie-Beam transition attached to an approximate 11-degree SSTR profile face (worst-case scenario), attachments at a lesser profile angle for the J and F barriers are deemed acceptable for the TxDOT transition design. Therefore, TTI recommends that the 10-gage Thrie Beam End Shoe transition bolt directly to the face of the J and F barriers (as modified in Figure 3-4 and Figure 3-5) without any wedge plate attachment.

TTI does not recommend using a built-up steel wedge plate for use on the “G” shape barrier transition. It is recommended that a MwRSF standardized buttress with shape transitioning from the “G” shape to the vertical wall, as described in Section 3.1.1, be used (ref. 8, 9). TTI recommends performing full-scale MASH TL-3 crash testing for transition shape details more severe/steep than what has been recommended by MwRSF.

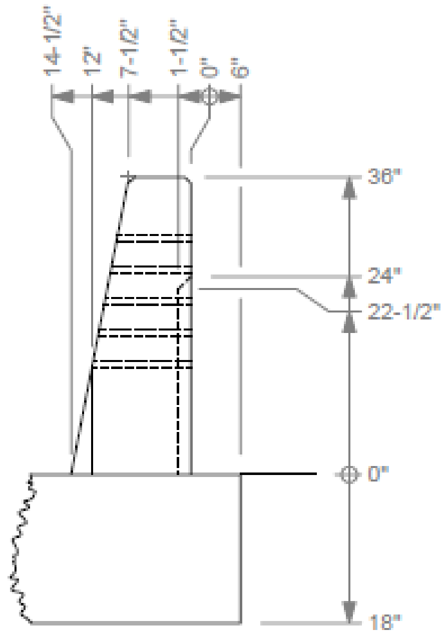


Figure 3-8 Section View of TxDOT Thrie-Beam Transition to Single Slope Barrier.

3.1.5 Minimum Barrier Height and Design Load and Application Height for End Post Designs

For a bridge barrier to be considered a MASH acceptable barrier, a minimum height must be met to ensure stability of the vehicle and to prevent override of the barrier. The MASH TL-3 minimum barrier height was determined to be 29 inches in NCHRP Project 20-07/Task 395, "MASH Equivalency of NCHRP Report 350-Approved Bridge Railings." The height of a bridge barrier is measured from the top of the roadway surface or overlay to the top of the barrier. Figure 3-9 shows two examples of how the height of a barrier (H) is measured.

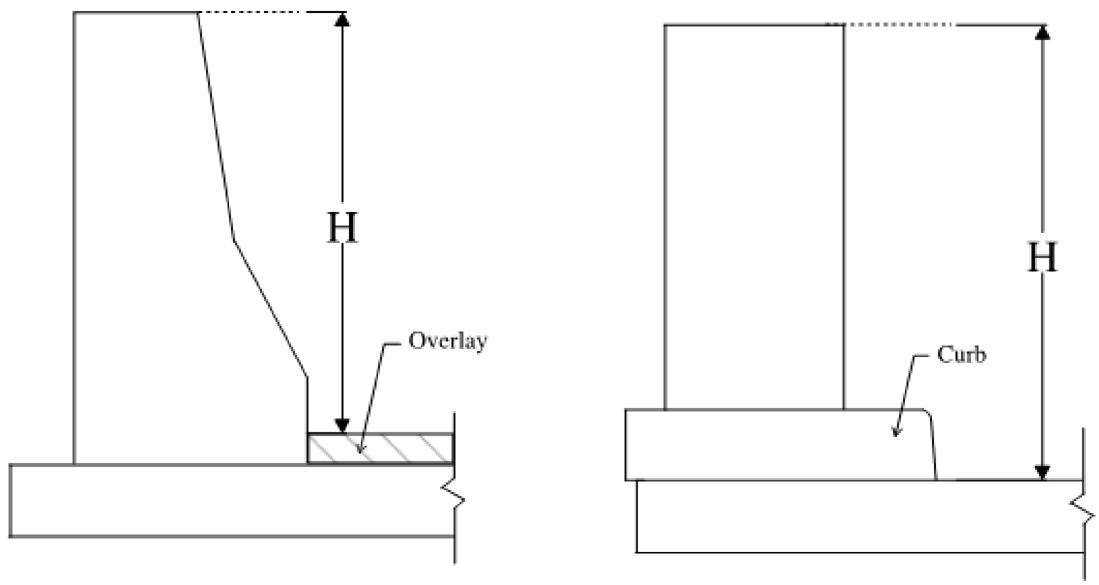


Figure 3-9 Examples of how the Height of a Barrier (H) is Measured.

To evaluate the structural adequacy of a barrier using only direct engineering analysis, an LRFD strength analysis must be conducted using the *AASHTO LRFD Bridge Design Specifications*, Section 13. The calculated strength of a bridge barrier must be greater than or equal to the MASH design impact load provided in Table 2.5. The Test Level 3 (TL-3) design impact load presented in *AASHTO LRFD Bridge Design Specifications*, Section 13 was not considered in this analysis since this design impact load is only applicable for NCHRP Report 350 impact conditions. The MASH TL-3 design impact load (F_t) found in NCHRP Project 20-07/Task 395 is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface or overlay and distributed over a length (L_t) of 4 ft as shown in Table 2.5. Figure 3-10 shows two examples of how the design impact load (F_t) is applied to a barrier.

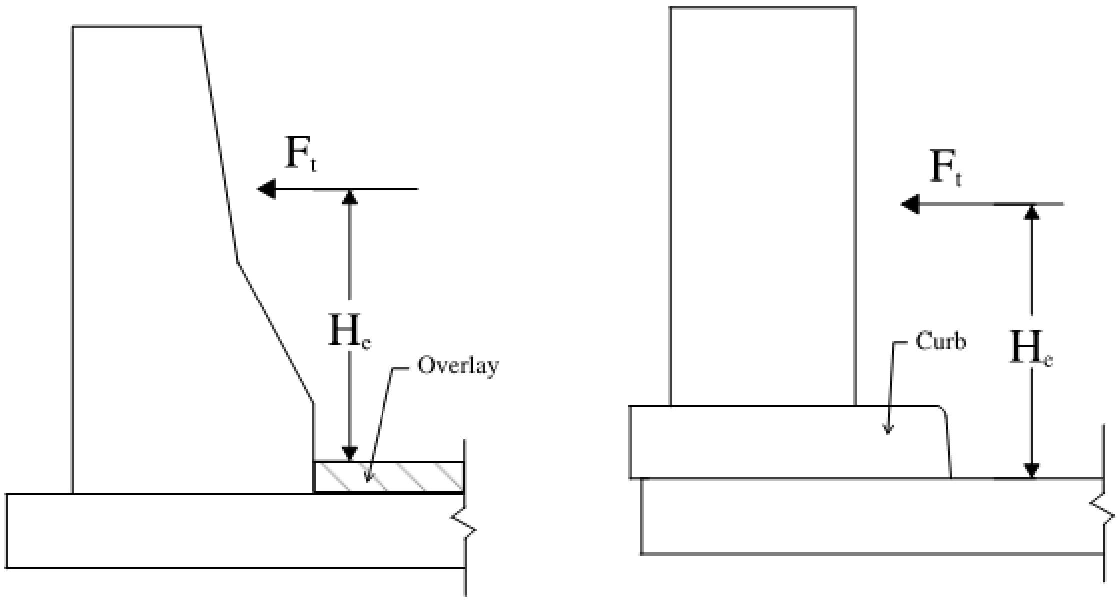


Figure 3-10 Examples of how the Design Impact Load (F_t) is Applied to a Barrier for Analysis & Design.

3.2 END POST RETROFIT WITH MOMENT SLAB

3.2.1 Design Load and Application Height for Moment Slab Design

As presented in Table 2.5, the MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface or overlay. Figure 3-10 shows two examples of how the design impact load (F_t) is applied to a barrier.

3.3 ONE-LINE RETROFITS

3.3.1 Minimum Barrier Height and Design Load and Application Height for MASH TL-3 Design

This section provides MnDOT with the minimum barrier height and MASH TL-3 design load and application height to design the following:

i. Retrofit slipped formed F-Shape on One-Line Rail designs.

ii. Retrofit cast-In-place vertical wall with vertical dowels into deck and curb

As stated in Section 3.1.5, the MASH TL-3 minimum barrier height is 29 inches. Figure 3-9 in Section 3.1.5 shows two examples of how the height of a barrier (H) is measured.

As presented in Table 2.5, the MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface or overlay. Figure 3-10 in Section 3.1.5 shows two examples of how the design impact load (F_t) is applied to a barrier.

3.3.2 Design Guidance for Max Exposed Width and Height of Curbs for MASH TL-3

A bridge barrier with a large curb height and/or exposed width can cause vehicle instability and high occupant risk values. Figure 3-11 shows an example of how the curb height and exposed curb width are measured.

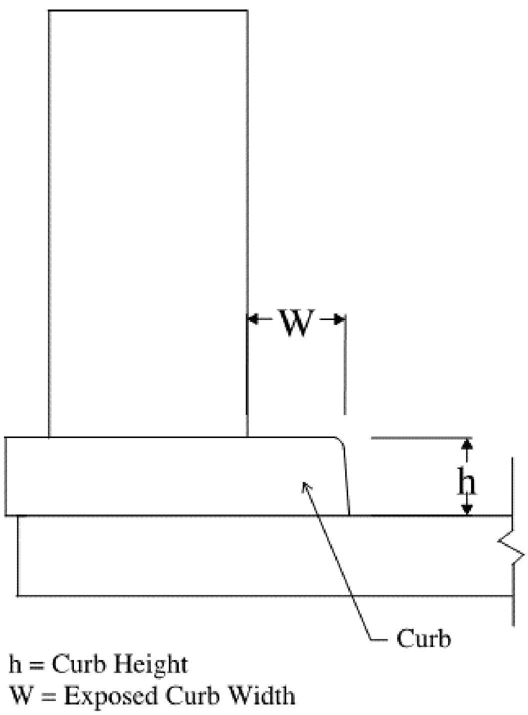


Figure 3-11 Example of how the Curb Height and Exposed Curb Width are Measured.

MASH Test 3-10 and MASH Test 3-11 were performed on a bridge rail system with a curb height of 10 inches and exposed width of 18 inches under project titled, "MASH TL-3 Evaluation of Louisiana Retrofit Post and Beam with Safety Walk Bridge Rail", TTI Report No. 606861-1&2. Due to excessive occupant ridedown accelerations during MASH Test 3-10, the Louisiana Retrofit Post and Beam with Safety Walk Bridge Rail did not perform acceptably for a MASH TL-3 longitudinal barrier. Therefore, due to the results from this test, TTI researchers recommend that MASH TL-3 bridge barriers with a curb height of 10 inches have a maximum exposed curb width of 9 inches. Curb heights greater than 10 inches have not been tested to MASH, therefore, TTI researchers cannot provide design guidance for curbs taller than 10 inches. Additionally, for MASH TL-3 bridge barriers with a curb height of 6 inches and 8 inches, TTI researchers recommend a maximum exposed curb width of 15 inches and 12 inches, respectively. Table 3.1 shows the maximum exposed curb widths that TTI researchers recommend for MASH TL-3 bridge barriers.

Table 3.1 Recommended Maximum Exposed Curb Widths for MASH TL-3 Bridge Barriers.

Curb Height, *h* (in.)	Maximum Exposed Curb Width, w (in.)
10	9
8	12
6	15

3.4 G BARRIER RETROFITS

3.4.1 Modification(s)/Removal of Existing Metal Posts and Rails Mounted on G Barriers

Based on the analysis conducted on G barriers under Task 2 of this project (see Chapter 2), all metal posts and rails mounted on G barriers must be removed to satisfy the geometric evaluation criteria specified in AASHTO LRFD Section 13 Figures A13.1.1-2 and A13.1.1-3. After removal, the height and strength requirements as previously described herein must be satisfied.

3.4.2 Minimum Barrier Height and Design Load and Application Height for MASH TL-3 Design

As stated in Section 3.1.5, the MASH TL-3 minimum barrier height is 29 inches. Figure 3-9 in Section 3.1.5 shows two examples of how the height of a barrier (H) is measured.

As stated in Section 3.1.5, the MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface or overlay. Figure 3-10 in Section 3.1.5 shows two examples of how the design impact load (F_t) is applied to a barrier.

3.4.3 HSS Tube Section Retrofit

Adding an HSS tube section retrofit to the top of a G barrier will increase the overall height and strength of the barrier system. The HSS tube section must provide a sufficient increase in total barrier system height (H) to ensure that the bridge barrier meets the MASH TL-3 minimum barrier height of 29 inches. Also, the HSS tube section retrofit must have adequate structural capacity to resist MASH TL-3 impact loads. TTI researchers recommend designing the HSS tube member and anchor bolt connection to resist a design impact load of 5.625 kip/ft acting at the centerline of the rail in the transverse direction over a length of 4.0 ft. This design impact load was calculated by analyzing the data from the Finite Element (FE) simulation analysis conducted under NCHRP Project 20-07/Task 395. As an example, Figure 3-12 shows a profile view of a barrier with a HSS tube section retrofit. For the design of the epoxy anchoring system for the G barrier retrofit, it is recommended that the manufacturer’s specification for the design of the adhesive anchors be followed. There may be factors that affect the strength of these adhesive anchors such as spacing, edge distance, temperature, etc. Use an adhesive anchorage with ¾” dia.

anchor rod in accordance with MnDOT spec 3385, Type C with hex nut and washer. Provide an adhesive with a minimum characteristic bond strength in uncracked concrete of 2.0 ksi and a minimum characteristic bond strength in cracked concrete of 1.2 ksi. Embed the anchorage no less than 6.5 inches regardless of characteristic bond strength. Drill through reinforcement (if encountered) to achieve minimum embedment. Ensure hex nut is in contact with adjacent surface and torque to 80 ft-lbs unless a higher torque is recommended by the manufacturer. Proof load to 2.2 kips. The analysis calculations for this HSS tube section retrofit design are shown in Appendix E2.

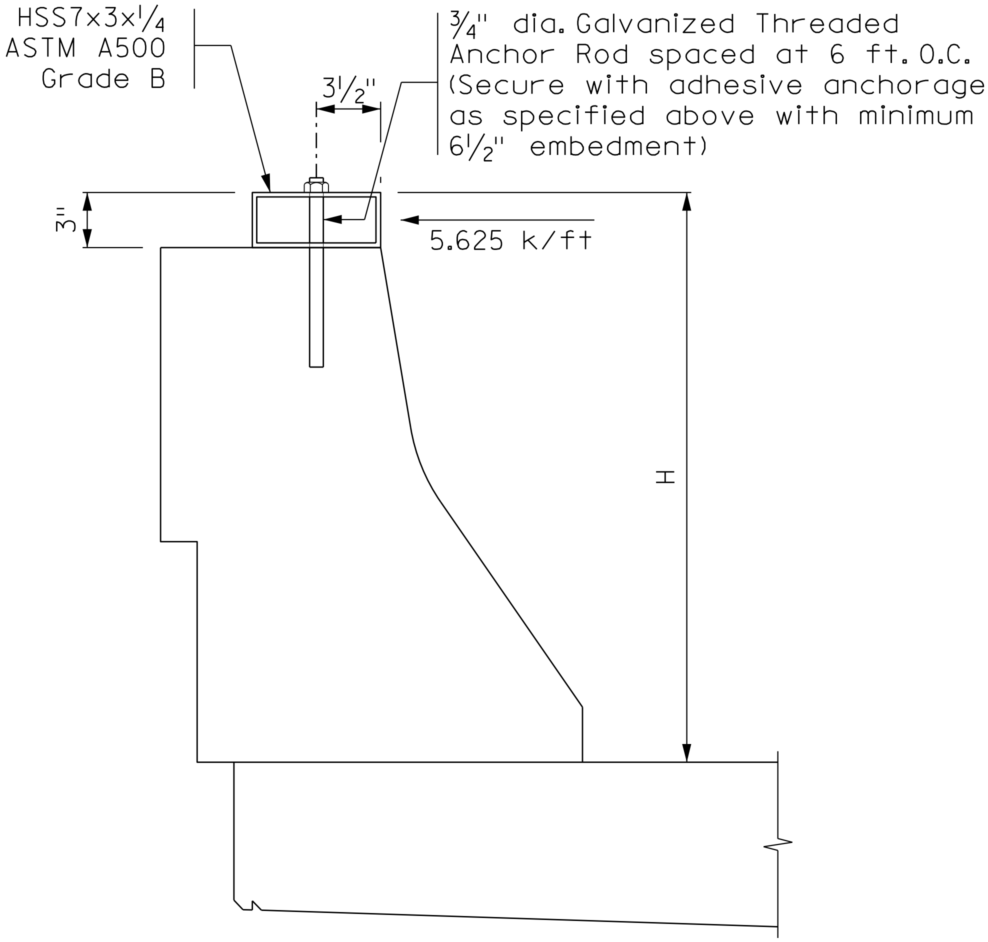


Figure 3-12 Profile View of Barrier with HSS Tube Section Retrofit.

3.4.4 Cast-In-Place Concrete Height Extension Retrofit

Adding a cast-in-place (CIP) concrete height extension (short concrete wall section) to the top of a barrier will increase the overall height and strength of a barrier system. The CIP concrete height extension must provide a sufficient increase in total barrier system height (H) to ensure that the bridge barrier meets the MASH TL-3 minimum barrier height of 29 inches. Also, the CIP concrete height extension must have adequate structural capacity to resist MASH TL-3 impact loads. TTI researchers recommend designing the concrete wall section and anchorage connection to resist a design impact load of 5.625 kip/ft acting at the centerline of the concrete wall section in the transverse direction over a length of 4.0 ft. As previously mentioned, this design impact load was calculated by analyzing the data from the Finite Element (FE) simulation analysis conducted under NCHRP Project 20-07/Task 395. As an example, Figure 3-13 shows a profile view of a barrier with a concrete wall section retrofit. For the design of the epoxy anchoring system for the G barrier retrofit, it is recommended that the manufacturer's specification for the design of the adhesive anchors be followed. There may be factors that affect the strength of these adhesive anchors such as spacing, edge distance, temperature, etc. Use an adhesive anchorage with a #5 dowel bar. Provide an adhesive with a minimum characteristic bond strength in uncracked concrete of 1.7 ksi and a minimum characteristic bond strength in cracked concrete of 1.3 ksi. Embed the anchorage no less than 6.5 inches regardless of characteristic bond strength. Drill through reinforcement (if encountered) to achieve minimum embedment. Proof load to 2.2 kips. The analysis calculations for this concrete wall section retrofit design are shown in Appendix E3.

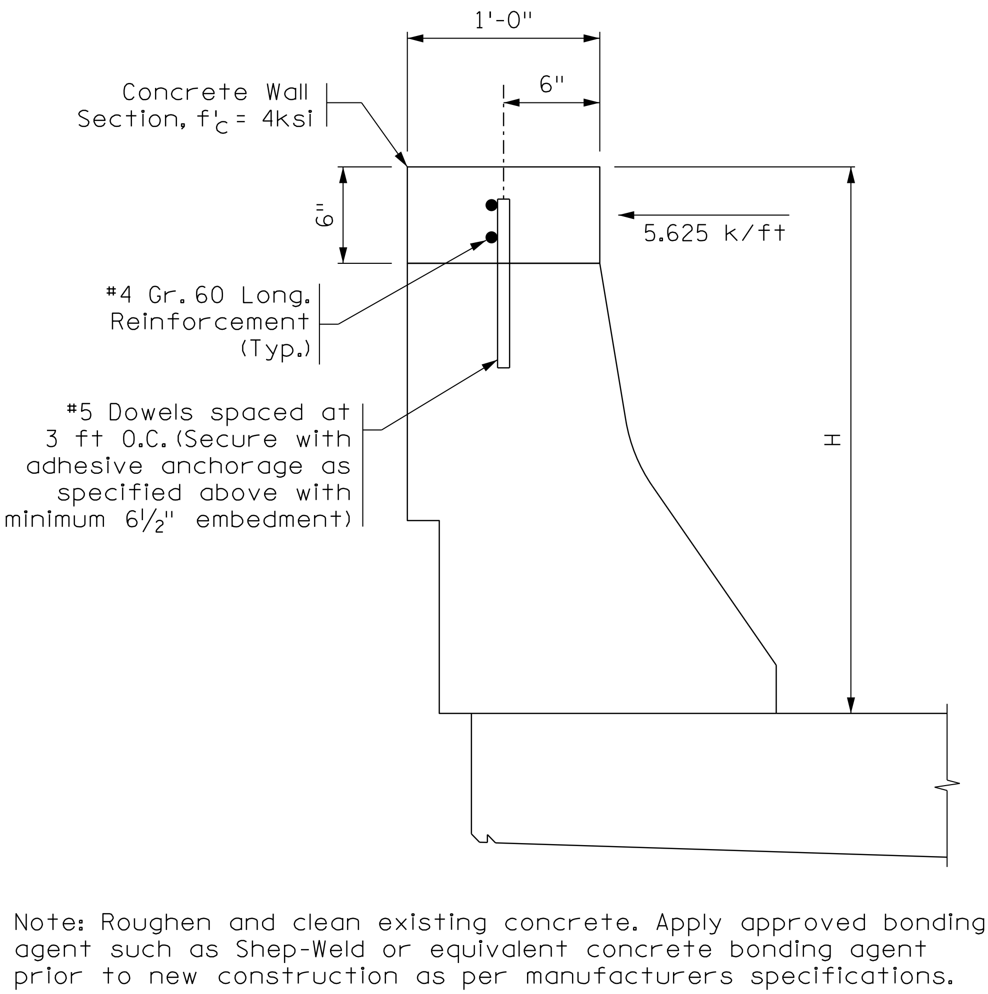


Figure 3-13 Profile View of Barrier with Concrete Wall Section Retrofit.

3.5 J AND F BARRIER RETROFITS

3.5.1 Minimum Barrier Height and Design Load and Application Height for MASH TL-3 Design

As stated in Section 3.1.5, the MASH TL-3 minimum barrier height is 29 inches. Figure 3-9 in Section 3.1.5 shows two examples of how the height of a barrier (H) is measured.

As stated in Section 3.1.5, the MASH TL-3 design impact load (F_t) is 71 kips located at an effective height (H_e) of 19 inches above the roadway surface or overlay. Figure 3-10 in Section 3.1.5 shows two examples of how the design impact load (F_t) is applied to a barrier.

If the MASH TL-3 barrier height requirement is satisfied and the MASH TL-3 strength requirement at mid-span and at ends/joints is satisfied, no retrofit is needed for J and F barriers.

3.6 CONCLUSIONS

Many Minnesota bridges have older barriers or parapets that met the design code at the time of Construction in the 1950's. Many of these bridge barriers no longer meet current strength and performance requirements of NCHRP Report 350 or Manual for Assessing Safety Hardware (MASH). As Minnesota Department of Transportation (MnDOT) begins to rehabilitate older existing bridges, a determination needs to be made as to whether the existing older barrier type can remain in place or if it should be rehabilitated or replaced with a newer style barrier.

Initially, the time periods and number of structures in the state that have One-Line Rails, type G, type J, and type F barriers were documented. Then evaluations of the structural strength and crashworthiness of each barrier type were performed. Following that, recommended guidance and evaluation criteria were developed to determine when an existing barrier should be upgraded or replaced to meet the requirement of MASH Test Level 3.

The primary objective of this project was to evaluate and improve the geometrics and strength of the barriers currently in use by MnDOT with respect to MASH Test Level 3 (TL-3) criteria. The research benefits from this project are as follows:

1. An analysis procedure was developed with respect to the current MASH TL-3 strength and performance criteria to evaluate the barriers investigated under this project. Section 2.2 of the Final Report provides detailed information of the analysis procedure.

2. Evaluation of the selected bridge barriers were performed using the analysis procedure. These barriers were evaluated for strength and performance (i.e., structural adequacy and occupant risk evaluation criteria) with respect to MASH TL-3 criteria. Summary tables for each barrier type were developed to present the summary of the analyses results for the barriers (see Table 2.1 through 2.3 in this report). Key findings from the evaluation are as follow:

- All One-Line Railings were found not satisfactory (NS) due a lack of structural adequacy in the end post and also due to the required geometric criteria for MASH TL-3.
- Barriers with metal post and rail attachments were found not satisfactory (NS) due to the geometric criteria with respect to MASH Requirements.
- Barriers with a separate end post with a width of 24 inches or less were found not satisfactory (NS) due a lack of structural adequacy in the end post.

3. Recommended guidance and evaluation criteria were developed for this project to determine when an existing barrier should be upgraded (i.e., retrofitted) or replaced.
4. Retrofit design options were developed for existing barriers found not satisfactory to meet MASH TL-3 criteria. Chapter 3 of this report provides detailed information of each retrofit option. The retrofit design options are as follows:

The methodology used for this project was as follows for the Type J and F, One line and Type G barrier types:

1. MCAD worksheets developed by TTI researchers were utilized to complete a thorough evaluation of the barrier systems according to the MASH TL-3 strength and performance criteria. Copies of these analyses are included in the appendix of this report.
2. TTI researchers made recommendations to improve the crash worthiness of barriers found not satisfactory (NS) with respect to MASH TL-3 criteria. Please refer to Chapter 3 of this report for additional information regarding barrier retrofit methodology and guidance for each barrier type.
3. TTI researchers developed retrofit design options for existing barriers found not satisfactory to meet MASH TL-3 criteria. The retrofit design options were developed using MCAD worksheets developed by TTI researchers.

The steps to implement this research for the barrier types evaluated for this project are as follows:

1. Review the specific project details with respect to the findings in this report.
2. For the evaluation of all end post conditions with respect to MASH TL-3 strength and performance criteria, please refer to Sections 3.1 and 3.2 for additional guidance and information.
3. For the evaluation of One-Line Barriers with respect to MASH TL-3 strength and performance criteria, please refer to section 3.3 for additional guidance and information.
4. For the evaluation of G-Barriers with respect to MASH TL-3 strength and performance criteria, please refer to section 3.4 for additional guidance and information.
5. For the evaluation of J and F Barriers with respect to MASH TL-3 strength and performance criteria, please refer to section 3.5 additional guidance and information.

REFERENCES

1. American Association of State Highway and Transportation Officials. (2016). *Manual for Assessing Safety Hardware, AASHTO Subcommittee on Bridges and Structures*. Washington, DC: AASHTO.

2. American Association of State Highway and Transportation Officials. (2017). *AASHTO LRFD Bridge Design Specifications* (8th Edition). Washington, DC: AASHTO Subcommittee on Bridges and Structures.

3. Bligh, R., W. Williams, C. Silvestri-Dobrovolny, N. Schulz, S. Moran, & T. Skinner. (2017). *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings* (Report No. 607141. NCHRP Project 20-07 Task 395). College Station, TX: Texas A&M Transportation Institute.

4. Bligh, R. P., J. L. Briaud, A. Abu-Odeh, D. O. Saez, L. S. Maddah, & K.M. Kim. (2017). *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* (NCHRP Project No. 22-20(2)). College Station,TX: Texas A&M Transportation Institute.

5. Polivka, K. A., R. K. Faller, D. L. Sicking, J. R. Rohde, B. W. Bielenberg, J. D. Reid, & B. A. Coon. (2006). *Performance Evaluation of the Permanent New Jersey Safety Shape Barrier – Update to NCHRP 350 Test No. 3-10 (2214NJ-1)* (NCHRP Project No. 22-14(2). Report No. TRP-03-177-06). Lincoln, NE: Midwest Roadside Safety Facility.

6. Bullard, D. L., R. P. Bligh, W. L. Menges, & R. R. Haug. (2010). *Evaluation of Existing Roadside Safety Hardware Using Manual for Assessing Safety Hardware (MASH)* (NCHRP Project No. 22-14(3). NCHRP Research Results Digest 349). College Station, TX: Texas A&M Transportation Institute.

7. Williams, W. F., J. Ries, R. P. Bligh, & W. Odell. (2017), *Design and Full-Scale Testing of Aesthetic TxDOT Type T224 Bridge Rail for MASH TL-5 Applications* (TRB Paper No. 17-06469). Washington, DC: Transportation Research Board.

8. Rosenbaugh, S. K., R. K. Faller, W. G. Fallet, & R. W. Bielenberg. (2019). *34-In Tall Thrie Beam Transition to Concrete Buttress* (Research Project No. TPF-5(193) Supplement #103, NDOT Sponsoring Agency Code RHE-17M). Lincoln, NE: Midwest Roadside Safety Facility, Nebraska Transportation Center, University of Nebraska-Lincoln.

9. Rosenbaugh, S. K., J. D. Schmidt, & R. K. Faller (2018). *Development of a Standardized Buttress for Approach Guardrail Transitions* (TRB Paper No. 18-05386). Washington, DC: Transportation Research Board.

To obtain a copy of the appendices, contact research.dot@state.mn.us, 651-366-3780.