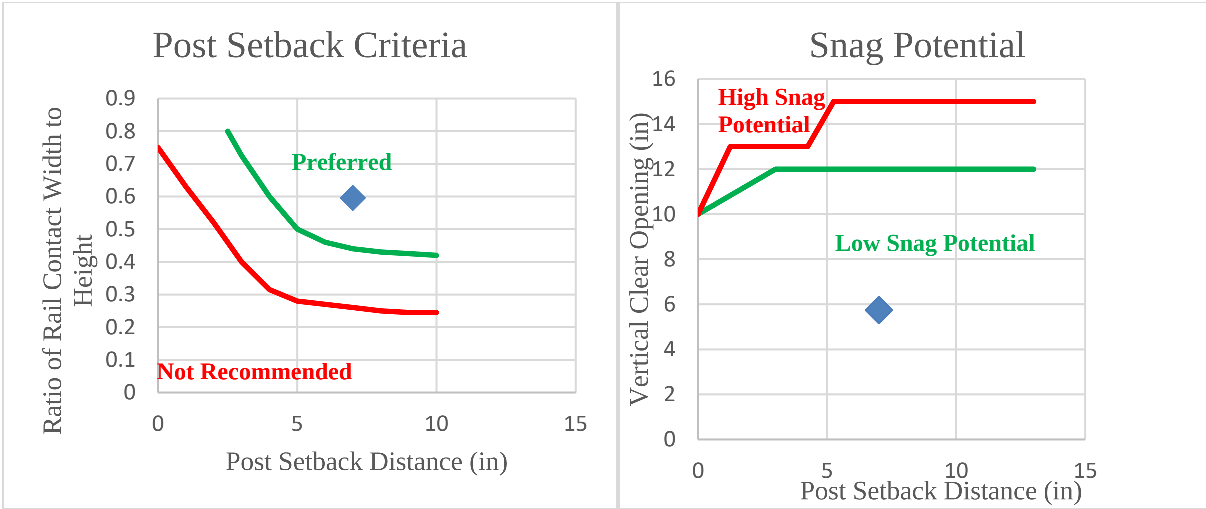
Oregon 3-Tube Bridge Rail MASH Test Level 4 Assessment

Overview
Texas A&M Transportation Institute (TTI) has completed the analysis study for the Oregon 3-Tube bridge rail system. TTI researchers have evaluated this bridge rail system for AASHTO MASH 2016 Test Level 4 (TL-4) compliance. The details and strength analysis spreadsheet for the Oregon 3-Tube bridge rail system is presented in Appendix A.

To evaluate the Oregon 3-Tube bridge rail system according to MASH 2016, three different criterions were considered. These criteria consist of stability, rail geometrics, and strength. The analysis methodologies used to evaluate these criteria for the Oregon 3-Tube bridge rail system are presented below along with a summary of the evaluation results and recommendations. The results of the analyses were used to determine whether the Oregon 3-Tube bridge rail system can be considered MASH TL-4 compliant or if the bridge rail system will require crash testing to establish MASH TL-4 compliance.

Stability Evaluation
For a bridge rail system to be considered a MASH acceptable barrier, a minimum height must be met to ensure stability of the vehicle. The minimum height requirement for a MASH TL-4 bridge rail system is 36 inches as previously specified for TxDOT Research Project 9-1002 "Roadside Safety Device Crash Testing Program,". The Oregon 3-Tube bridge rail system has a height of 42 inches. Therefore, the Oregon 3 Tube bridge rail system meets the MASH TL-4 stability criterion (Satisfactory).

Rail Geometrics Evaluation
Post setback distance, ratio of contact width to height, and vertical clear opening were determined for the Oregon 3-Tube bridge rail system. The appropriate data points were plotted against the current AASHTO LRFD Section 13 geometric relationships. As seen in Figure 1 the rail geometrics plot in the acceptable regions. Since the calculated resistance is equal to or greater than the design impact load, the Oregon 3-Tube bridge rail system meets MASH TL-4 structural adequacy criterion (Satisfactory).



(a) Post Setback Criteria (b) Snag Potential

Figure 1: Oregon 3-Tube Bridge Rail Geometrics Plot

Strength Evaluation

The plastic resistance of all metal rails contributing to an inelastic hinge mechanism in the rail (denoted M_p in AASHTO Section 13, but denoted M_{rail} in the spreadsheet) is calculated.

Steel post and beam bridge rails systems can have several possible failure modes that control the resistance of a post. Therefore additional checks are required to obtain the limiting post strength. The failure mechanisms considered for use in this spreadsheet template are those observed to be critical in full-scale crash tests. These include plastic strength of the post (denoted P_{p1} in the spreadsheet), ultimate strength of the anchor bolts, weld strength of the post and baseplate weld connection, and concrete section capacity in the block shear zone of the anchor bolts.

The post strength (P_p) value used in the AASHTO Section 13 equations is taken as the limiting post strength of the relevant failure mechanisms. The total resistance of the railing (denoted R in AASHTO Section 13 and the spreadsheet) is calculated using AASHTO Section 13 Equation A13.3.2-3 (Equation 1).

$$R = \frac{2M_p + 2P_p L\left(\sum_{i=1}^{N} i\right)}{2NL - L_t}$$

Equation 1

where:

R = Total ultimate resistance, i.e., nominal resistance, of the railing (kips)
L = Post spacing or single span (ft.)

M_p (denoted M_{rail} on spreadsheet) = Inelastic or yield line resistance of all rails contributing to a plastic hinge (kip-ft).
N = Number of railing spans.

The calculated strength of the Oregon 3-Tube bridge rail system was compared to the TL-4 design impact load provided in Table A13.2-1 of AASHTO LRFD Bridge Design Specifications, Section 13 and the TL-4 design impact load provided in Table 4.2 of the research report prepared under NCHRP Project 20-07 Task 395. Complete structural details of the bridge rail system were required for this task.

The Oregon 3-Tube bridge rail system has a calculated resistance of 86 kips at an effective height (H_e) of 30 inches above the roadway surface. The TL-4 design impact load (F_t) in Table A13.2-1 of AASHTO LRFD Bridge Design Specifications, Section 13 is 80 kips located at an effective height (H_e) of 30 inches above the roadway surface. Since the calculated resistance is equal to or greater than the design impact load, the Oregon 3-Tube bridge rail system meets MASH TL-4 structural adequacy criterion when evaluated to the TL-4 design impact load in AASHTO LRFD Bridge Design Specifications, Section 13 (Satisfactory).

Recommendation

As summarized in Table 1, the Oregon 3-Tube bridge rail system from Oregon does satisfy all MASH TL-4 criteria.

Table 1 Summary of Assessment of Oregon 3-Tube.

	Required	**Actual**	**Assessment**
Stability	36 in.	42 in.	**Satisfactory**
Rail Geometrics	See Figure 1		**Satisfactory**
Strength	80 kips	86 kips	**Satisfactory**

References

1. H.E. Ross, D.L. Sicking, R.A. Zimmer, and J.D. Michie, *Recommended Procedures for the Safety Performance Evaluation of Highway Features, National Cooperative Highway Research Program Report 350*, Transportation Research Board, National Research Council, Washington, D.C., 1993.

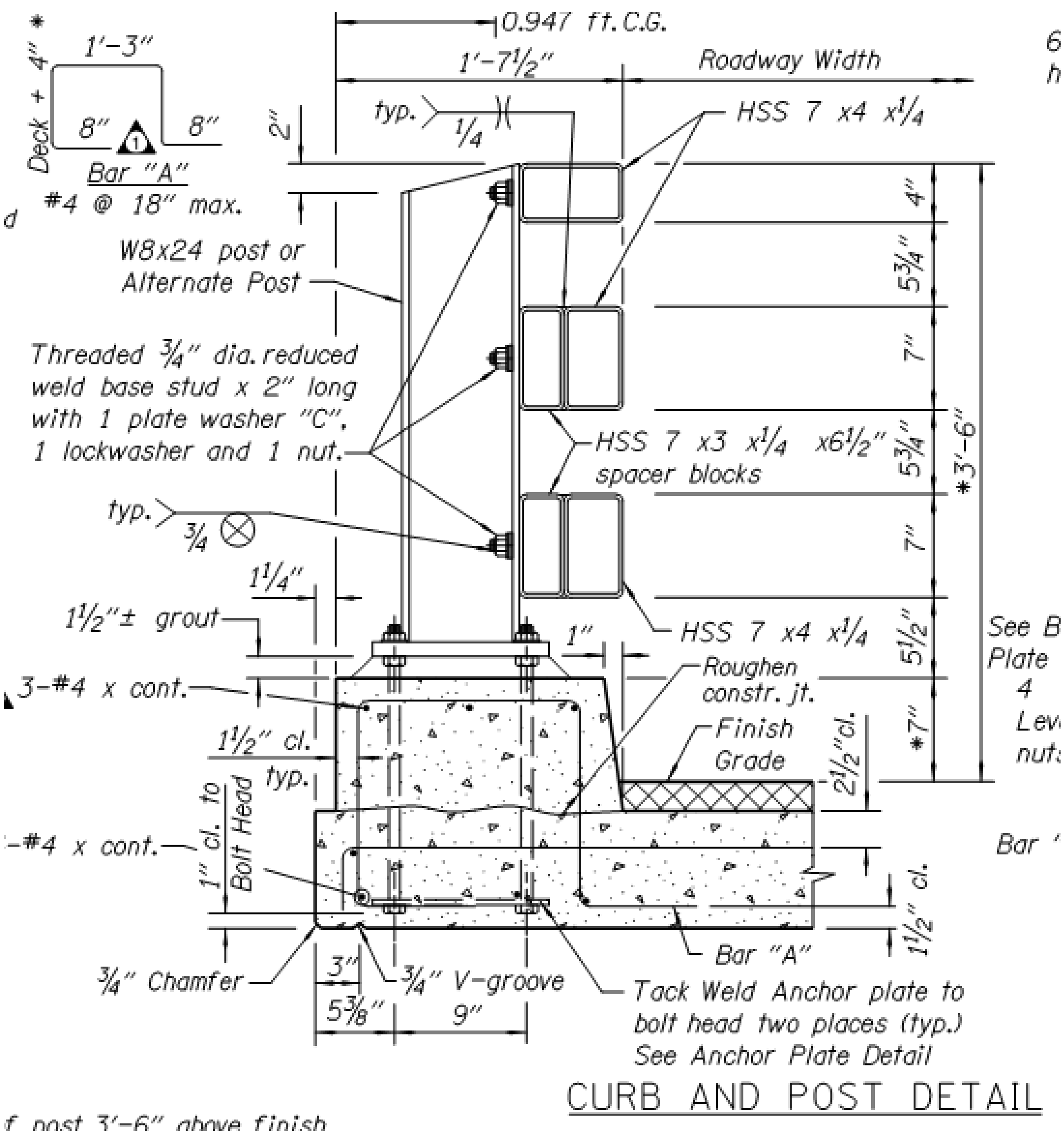
2. American Association of State Highway and Transportation Officials, *Manual for Assessing Safety Hardware*, AASHTO Subcommittee on Bridges and Structures, Washington, D.C., 2016.

3. R. Bligh, W. Williams, C. Silvestri-Dobrovolny, N. Schulz, S. Moran, and T. Skinner, *MASH Equivalency of NCHRP Report 350-Approved Bridge Railings*, Report No. 607141, Texas A&M Transportation Institute, College Station, Texas, 2017.

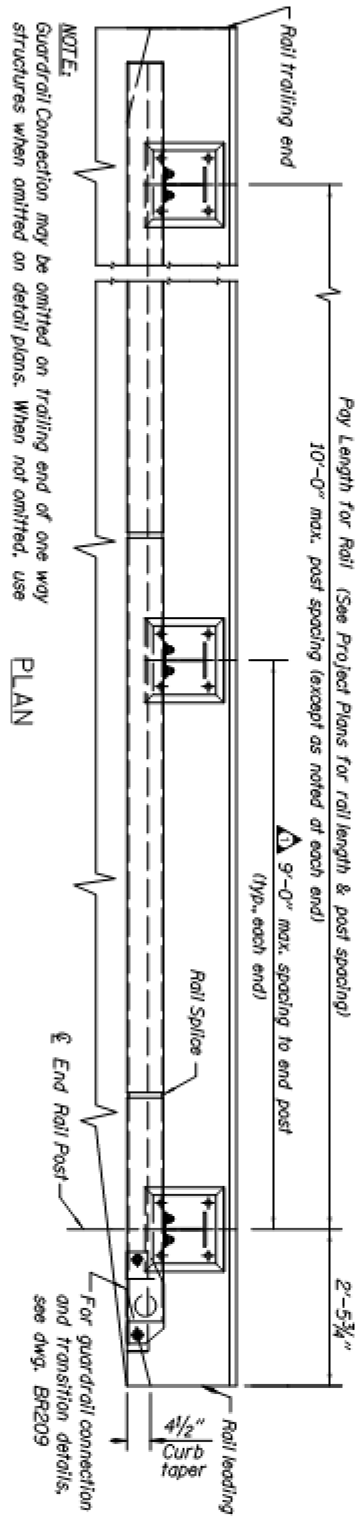
4. Williams, W.F., R.P. Bligh, and W.L. Menges. *MASH Test 3-11 of the TxDOT T222 Bridge Rail*. Report No. 9-1002-12-13. Texas A&M Transportation Institute, College Station, Texas, 2014.

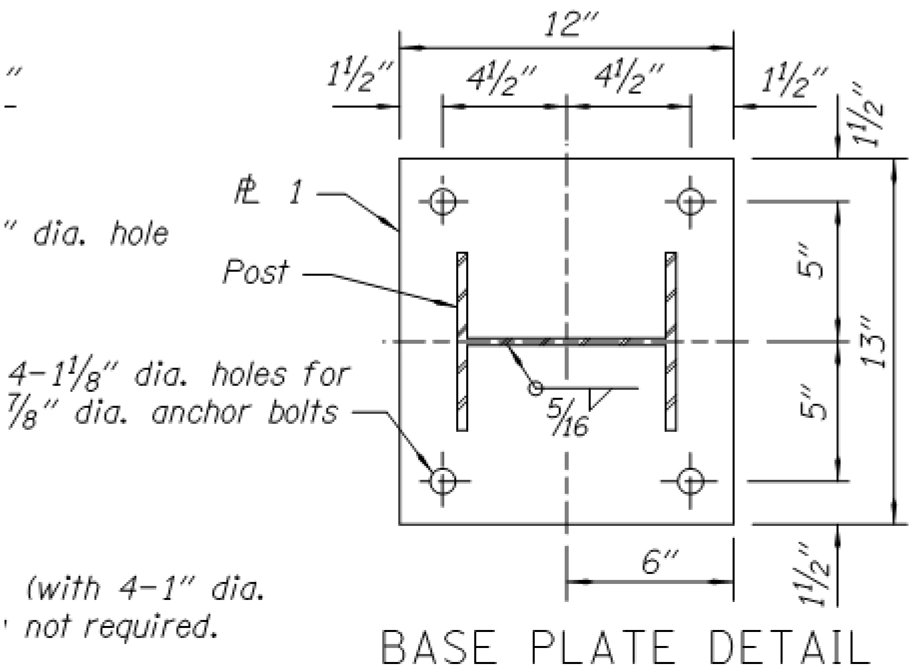
APPENDIX A: OREGON 3-TUBE DETAILS AND STRENGTH ANALYSIS

Given Proposed Design Details:



CURB AND POST DETAIL


Rail trailing end
Pay Length for Rail (See Project Plans for rail length & post spacing)
10'-0" max. post spacing (except as noted at each end)
1 9'-0" max. spacing to end post
(typ. each end)
Rail Splice
℄ End Rail Post
2'-5¾"
4½"
Curb taper
Rail leading
For guardrail connection and transition details, see dwg. BR209
NOTE:
Guardrail Connection may be omitted on trailing end of one way structures when omitted on detail plans. When not omitted, use
PLAN


12″
1½″
4½″
4½″
1½″
1½″
℄ 1
″ dia. hole
Post
4–1⅛″ dia. holes for
⅞″ dia. anchor bolts
5/16
5″
5″
13″
6″
1½″
(with 4–1″ dia.
not required.
BASE PLATE DETAIL

Texas A&M Transportation Institute

SUBJECT: **Oregon 3-Tube MASH TL-4 Bridge Rail LRFD Strength Analysis**

General Information:

1) Concrete Parapet Strength, f'c = 3300psi
2) Anchor Rods are HS Gr. 105 Material ϕ7/8" x 16" , Fu=105ksi
3) All concrete reinforcing steel = Grade 60
4) Plates are 3/8in. x 13in. x 12in., A36 Material, Fy=36ksi
5) Posts are W8x24, A36 Material, Fy=36ksi
6) HSS7x4x1/4 rails are A500 Grade B Material, Fy=46ksi
7) Reference: AASHTO LRFD Bridge Design Specifications, Section 13, TL-4 Conditions.
8) Calculate the Strength of the Rail based on Worst Case Rail Strength and AASHTO LRFD Section 13 Strength Requirements.

************* **Concrete, Reinforcing Steel & Structural Shape Information** *************

$f'_c := 3300 \cdot psi$ Compressive Strength of Concrete (psi)

$F_y := 46ksi$ Yield Strength of Steel Rails (ksi)

$F_{yp} := 36ksi$ Yield Strength of Steel Posts (ksi)

$F_{yBP} := 36ksi$ Yield Strength of Plates (ksi)

$f_y := 60ksi$ Yield Strength of Concrete Reinforcing Steel, (ksi)

$\phi := 1.0$ Concrete Strength Reduction Factor

$E_c := 3400000psi$ Modulus of Elasticity of Concrete (psi)

$E_s := 29000ksi$ Modulus of Elasticity of Steel (ksi)

**************************** **Anchor Rod Properties** ****************************

$F_{u.rod} := 105ksi$ Tensile Strength of Anchor Rods (ksi)

$d_{rod} := \frac{7}{8} in$ Diameter of Anchor Rods (in)

$A_{rod} := \frac{\pi \cdot d_{rod}^2}{4} = 0.6 \cdot in^2$ Area of a Anchor rod (in^2)

$N_{rod} := 4$ Number of Rods

Reduction Factors for Anchor Rods: $\phi_t := 1.0$ (0.75) $\phi_v := 0.75$ (0.65)

AASHTO LRFD Bridge Design Specification for Required Test Level

Table A13.2-1 - Design Forces for Traffic Railings

Test Level	F_t (kip)	F_L (kip)	F_v (kip)	L_t/L_L (ft)	L_v (ft)	H_e (in)	H_{min} (in)
TL 1	13.5	4.5	4.5	4.0	18.0	18.0	18.0
TL 2	27.0	9.0	4.5	4.0	18.0	20.0	18.0
TL 3	71.0	18.0	4.5	4.0	18.0	19.0	29.0
TL 4 (a)	68.0	22.0	38.0	4.0	18.0	25.0	36.0
TL 4 (b)	80.0	27.0	22.0	5.0	18.0	30.0	36.0
TL 5 (a)	160.0	41.0	80.0	10.0	40.0	35.0	42.0
TL 5 (b)	262.0	75.0	160.0	10.0	40.0	43.0	42.0
TL 6	175.0	58.0	80.0	8.0	40.0	56.0	90.0

Note: (a) and (b) denote different TL 4 and TL 5 design force values for bridge rails of different heights.

$\mathbf{TL := 4}$ Test Level

$\mathbf{F_t := 80kip}$ Transverse Force

$\mathbf{F_L := 27kip}$ Longitudinal Force on Rail

$\mathbf{F_v := 22kip}$ Vertical Force on Rail

$\mathbf{L_t := 5ft}$ Longitudinal Length of Distribution of Impact Force

$\mathbf{L_L := 5ft}$ Length of Longitudinal Force on Rail

$\mathbf{L_v := 18ft}$ Length of Vertical Force on Rail

$\mathbf{H_e := 30in}$ Height of Equivalent Transverse Load

$\mathbf{L_p := 10ft}$ Spacing of Posts (ft.)

$\mathbf{H_t := 42in}$ Total Height of Bridge Rail System measured from Roadway Surface to top of highest rail (in.)

$\mathbf{h_{overlay} := 2.5in}$ Height of Asphalt Overlay (in.)

Bridge Rail & Post Strength Analysis:

Steel Rail Properties and Dimensions:
a) Steel Rails are HSS7x4x1/4 members
b) Steel Rails are A500 Gr. B Material, Fy=46ksi
c) Top Steel Rail bends about the x-axis
d) Bottom Two Steel Rails bend about the y-axis

$F_y = 46 \cdot ksi$ — Yield Strength of Steel Rails (ksi)

$Z_1 := 10.8in^3$ — Plastic Sectional Modulus of the Top Rail (in^3)

$Z_2 := 7.33in^3$ — Plastic Sectional Modulus of the Middle Rail (in^3)

$Z_3 := 7.33in^3$ — Plastic Sectional Modulus of the Bottom Rail (in^3)

$M_{R1} := F_y \cdot Z_1 = 41.4 \cdot kip \cdot ft$ — Plastic Moment Strength of Top Rail (k-ft)

$M_{R2} := F_y \cdot Z_2 = 28.1 \cdot kip \cdot ft$ — Plastic Moment Strength of Middle Rail (k-ft)

$M_{R3} := F_y \cdot Z_3 = 28.1 \cdot kip \cdot ft$ — Plastic Moment Strength of Bottom Rail (k-ft)

$M_{rail} := M_{R1} + M_{R2} + M_{R3} = 97.6 \cdot kip \cdot ft$ — Plastic Moment Strength of all Rails (k-ft)

$Y_{R1} := 40in$ — Height of Top Rail measured from top of asphalt overlay to centroid of rail (in.)

$Y_{R2} := 28.75in$ — Height of Middle Rail measured from top of asphalt overlay to centroid of rail (in.)

$Y_{R3} := 16in$ — Height of Bottom Rail measured from top of asphalt overlay to centroid of rail (in.)

$$Y_{bar} := \frac{Y_{R1} \cdot M_{R1} + Y_{R2} \cdot M_{R2} + Y_{R3} \cdot M_{R3}}{M_{rail}} = 29.85 \cdot in$$

Height of Resultant Force of all Rails (in.)

Steel Post and Base Plate Properties and Dimensions:
a) Steel Posts are A36 Material, Fy=36 ksi
b) Base Plates are A36 Material, Fy=36ksi
c) Base Plates are 3/8in. thick by 13in. long by 12in. wide

$w_{BP} := 12in$ — Width of Base Plate (in.)

$l_{BP} := 13in$ — Length of Base Plate (in.)

$t_{BP} := \frac{3}{8}in$ — Thickness of the Base Plate (in.)

$c_{rod} := 1.5in$ — Cover of Rods measured form the end of the Base Plate to the centroid of the Rods (in.)

$t_{grout} := 1.5in$ — Thickness of Grout (in.)

$h_{curb} := 7in$ — Height of Curb measured from the top of the Asphalt Overlay (in.)

$Y_{bar} = 29.85 \cdot in$ — Height of Resultant Force of all Rails (in.)

$h_p := Y_{bar} - t_{BP} - t_{grout} - h_{curb} = 20.98 \cdot in$ — Height measured from the Top of the Base Plate to the Resultant Force of Rails (in.)

$h_{BP} := h_p + t_{BP} = 21.35 \cdot in$ — Height measured from the Bottom of the Base Plate to the Resultant Force of Rails (in.)

Calculate the Plastic Strength of the Post: (P_{p1})

$Z_{post} := 23.1in^3$ — Plastic Sectional Modulus of Post about strong axis (in^3)

$F_{yp} = 36 \cdot ksi$ — Yield Strength of Post (ksi)

$M_{post} := Z_{post} \cdot F_{yp} = 69.3 \cdot kip \cdot ft$ — Plastic Moment Resistance of a Single Post (k-ft)

$$P_{p1} := \frac{M_{post}}{h_p} = 39.64 \cdot kip$$

Calculate the Post Strength based on the Ultimate Strength of the Anchor Rods: (P_{p2})

$\phi_t = 1 \qquad \phi_v = 0.75$	Strength Reduction Factors Used for Shear & Tension
$N_{rod.tension} := 2$	Number of Anchor Rods in Tension
$A_{rod} = 0.6 \cdot in^2$	Area of One Anchor Rod (in^2)
$h_p = 20.98 \cdot in$	Height measured from the top of the Base Plate to the Resultant Force of all Rails (in.)
$F_{u.rod} = 105 \cdot ksi$	Tensile Strength of Anchor Rods (ksi)
$R_{nt} := \phi_t \cdot F_{u.rod} \cdot (0.75 \cdot A_{rod}) = 47.35 \cdot kip$	Nominal strength of One Rod in Tension (kip)
$R_{nv} := \phi_v \cdot F_{u.rod} \cdot (0.45 \cdot A_{rod}) = 21.31 \cdot kip$	Nominal strength of One Rod in Shear w/h threads in shear plane (kip)
$w_{rod} := w_{BP} - c_{rod} - \frac{1}{2} in = 10 \cdot in$	Distance From Rods in Tension to the Resultant Base Plate Bearing Stress (in.)
$M_{pt} := w_{rod} \cdot R_{nt} \cdot N_{rod.tension} = 78.92 \cdot kip \cdot ft$	Moment Strength of Post based on the Ultimate Strength of the Anchor Rods (k-ft)
$P_{p2t} := \frac{M_{pt}}{h_p} = 45.15 \cdot kip$	Ultimate Tensile Strength of Anchor Rods (kip)
$P_{p2v} := R_{nv} \cdot N_{rod} = 85.24 \cdot kip$	Ultimate Shear Strength of Anchor Rods (kip)

$$P_{p2} := \min\left(P_{p2t}, P_{p2v}\right) = 45.15 \cdot kip$$

Calculate the Post Strength based on the Lateral Punching Shear Resistance of Concrete from Traffic Side Anchor Rods: (P_{p3})

$\phi_v = 0.75$ — Shear Strength Reduction Factor

$A_{lat.back} := 306.5 in^2$ — Area of Back Failure Plane due to Anchor Rod Lateral Punching Shear (in^2) - Measured in SolidWorks

$A_{lat.side} := 93 in^2$ — Area of One Side Failure Plane due to Anchor Rod Lateral Punching Shear (in^2) - Measured in SolidWorks

$A_{lat.tot} := A_{lat.back} + 2 \cdot A_{lat.side} = 492.5 \cdot in^2$ — Total Area of Failure Planes due to Anchor Rod Lateral Punching Shear (in^2)

$V_{c.lat} := \phi_v \cdot 2 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi = 86.17 \cdot psi$ — Concrete Stress from LPS of Anchor Rods (psi)

$$P_{p3} := A_{lat.tot} \cdot V_{c.lat} = 42.44 \cdot kip$$

Calculate the Post Strength based on the Weld Strength of the Post and Baseplate Weld Connection: (P_{p4})

Reference: Table 5-Properties of Weld Treated as a Line, Design of Welded Structures, Omer W. Blodgett,1982, pg. 7.4-7

$\phi_{dynamic} := 1.5$ — Dynamic Impact Factor

$t_{weld} := \frac{5}{16} in$ — Weld Size (in.)

$F_{EXX} := 70 ksi$ — Weld Strength (ksi)

$b_f := 6.5 in$ — Width of W8x24 Post Flange (in.)

$d := 7.93 in$ — Depth of W8x24 Post (in.)

$t_w := 0.707 \cdot t_{weld} = 0.22 \cdot in$ — Factored Weld Size (in.)

$h_p = 20.98 \cdot in$ — Height measured from top of baseplate to Resultant Force of Rails (in.)

$S_w := t_w \cdot \left(b_f \cdot d + \frac{d^2}{3} \right) = 16.02 \cdot in^3$ — Sectional Modulus of Weld Section (in^3)

$M_{weld} := \phi_{dynamic} \cdot 0.6 \cdot F_{EXX} \cdot S_w = 84.1 \cdot kip \cdot ft$ — Moment Due to Welds (k-ft)

$$P_{p4} := \frac{M_{weld}}{h_p} = 48.11 \cdot kip$$

SUBJECT: **Oregon 3-Tube MASH TL-4 Bridge Rail LRFD Strength Analysis**

Find Post Strength by Using the Limiting ("Worst Case") Post Strength: P_p

$P_{p1} = 39.64 \cdot kip$

Plastic Strength of the Post

$P_{p2} = 45.15 \cdot kip$

Post Strength based on Ult. Strength of Anchor Rods

$P_{p3} = 42.44 \cdot kip$

Post Strength based on the Lateral Punching Shear Resistance of Concrete from Traffic Side Anchor Rods

$P_{p4} = 48.11 \cdot kip$

Post Strength based on the Weld Strength of the Post and Baseplate Weld Connection

$$P_p := \min\left(P_{p1}, P_{p2}, P_{p3}, P_{p4}\right) = 39.64 \cdot kip$$

Total Ultimate Resistance (Nominal Resistance) of Railing: R_R

One Span Failure Mode: N_1=1

$P_p = 39.64 \cdot kip$

$N_1 := 1$

$M_{rail} = 97.6 \cdot kip \cdot ft$

$L_p = 10 \cdot ft$

$L_t = 5 \cdot ft$

$$R_1 := \frac{16 \cdot M_{rail} + (N_1 - 1) \cdot (N_1 + 1) \cdot P_p \cdot L_p}{2 \cdot N_1 \cdot L_p - L_t} = 104.1 \cdot kip$$

Two Span Failure Mode: N_2=2

$P_p = 39.64 \cdot kip$

$N_2 := 2$

$M_{rail} = 97.6 \cdot kip \cdot ft$

$L_p = 10 \cdot ft$

$L_t = 5 \cdot ft$

$$R_2 := \frac{16 \cdot M_{rail} + {N_2}^2 \cdot P_p \cdot L_p}{2 \cdot N_2 \cdot L_p - L_t} = 89.92 \cdot kip$$

Total Ultimate Resistance (Nominal Resistance) of Railing: R_R

Three Span Failure Mode: N_3=3

$P_p = 39.64 \cdot kip$

$N_3 := 3$

$M_{rail} = 97.6 \cdot kip \cdot ft$

$L_p = 10 \cdot ft$

$L_t = 5 \cdot ft$

$$R_3 := \frac{16 \cdot M_{rail} + (N_3 - 1) \cdot (N_3 + 1) \cdot P_p \cdot L_p}{2 \cdot N_3 \cdot L_p - L_t} = 86.06 \cdot kip$$

Four Span Failure Mode: N_4=4

$P_p = 39.64 \cdot kip$

$N_4 := 4$

$M_{rail} = 97.6 \cdot kip \cdot ft$

$L_p = 10 \cdot ft$

$L_t = 5 \cdot ft$

$$R_4 := \frac{16 \cdot M_{rail} + N_4^{\,2} \cdot P_p \cdot L_p}{2 \cdot N_4 \cdot L_p - L_t} = 105.4 \cdot kip$$

Total Ultimate Resistance (Nominal Resistance) of Railing: R_R

Five Span Failure Mode: $N_5=5$

$$P_p = 39.64 \cdot kip$$

$$N_5 := 5$$

$$M_{rail} = 97.6 \cdot kip \cdot ft$$

$$L_p = 10 \cdot ft$$

$$L_t = 5 \cdot ft$$

$$R_5 := \frac{16 \cdot M_{rail} + (N_5 - 1) \cdot (N_5 + 1) \cdot P_p \cdot L_p}{2 \cdot N_5 \cdot L_p - L_t} = 116.59 \cdot kip$$

Six Span Failure Mode: $N_6=6$

$$P_p = 39.64 \cdot kip$$

$$N_6 := 6$$

$$M_{rail} = 97.6 \cdot kip \cdot ft$$

$$L_p = 10 \cdot ft$$

$$L_t = 5 \cdot ft$$

$$R_6 := \frac{16 \cdot M_{rail} + N_6^{\,2} \cdot P_p \cdot L_p}{2 \cdot N_6 \cdot L_p - L_t} = 137.68 \cdot kip$$

SUBJECT: **Oregon 3-Tube MASH TL-4 Bridge Rail LRFD Strength Analysis**

Total Ultimate Resistance (Nominal Resistance) of Railing: R_R

Note: The Total Ultimate Resistance of the bridge rail system is the minimum value of R_1 - R_6

$$R_r := \min(R_1, R_2, R_3, R_4, R_5, R_6) = 86.06 \cdot kip$$

Total Ultimate Resistance of the bridge rail system @ y_{bar} (kip)

$$H_e = 30 \cdot in$$

Height of Impact Force measured from the top of the roadway surface (in.)

$$Y_{bar} = 29.85 \cdot in$$

Height of the Resultant Force of all Rails measured from the top of the roadway surface (in.)

$$F_t = 80 \cdot kip$$

Impact Load @ H_e (kip)

$$R_R := R_r \cdot \left(\frac{Y_{bar}}{H_e}\right) = 85.63 \cdot kip$$

Total Ultimate Resistance of the bridge rail system @ H_e (kip)

CHECK= "OK", since $R_R = 85.6$ kips > $F_t = 80$ kips,

Conclusion: Bridge Rail System is Satisfactory for MASH TL-4