Implementation of crash simulation technology to validate the design impact loads for concrete bridge railings under “MASH”

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Background

Current Bridge Railing Design Practice

• Railing Design per AASHTO LRFD Bridge Design Specifications – Chapter 13

• Intended for design of rails to be crash tested (but not a substitute for crashworthiness)

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

<table>
<thead>
<tr>
<th>Design Forces and Designations</th>
<th>TL-1</th>
<th>TL-2</th>
<th>TL-3</th>
<th>TL-4</th>
<th>TL-5</th>
<th>TL-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_t$ Transverse (kips)</td>
<td>13.5</td>
<td>27.0</td>
<td>54.0</td>
<td>54.0</td>
<td>124.0</td>
<td>175.0</td>
</tr>
<tr>
<td>$F_L$ Longitudinal (kips)</td>
<td>4.5</td>
<td>9.0</td>
<td>18.0</td>
<td>18.0</td>
<td>41.0</td>
<td>58.0</td>
</tr>
<tr>
<td>$F_v$ Vertical (kips) Down</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>18.0</td>
<td>80.0</td>
<td>80.0</td>
</tr>
<tr>
<td>$L_t$ and $L_L$ (ft)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>3.5</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>$L_v$ (ft)</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>40.0</td>
<td>40.0</td>
</tr>
<tr>
<td>$H_e$ (min) (in.)</td>
<td>18.0</td>
<td>20.0</td>
<td>24.0</td>
<td>32.0</td>
<td>42.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Minimum $H$ Height of Rail (in.)</td>
<td>27.0</td>
<td>27.0</td>
<td>27.0</td>
<td>32.0</td>
<td>42.0</td>
<td>90.0</td>
</tr>
</tbody>
</table>
Background

Impacts to Railing Design Loads under MASH

- TL-1, 2 & 3 – considered minor due to increase in vehicle mass (~33%) & impact angle but no change in velocity.
- TL-4 – considered significant due to increase in both vehicle mass & impact velocity, i.e., impact severity increased by 56%.
- TL-5 & 6 – no change in testing criteria.
Background

- **Recommended Loads Table by TTI**

<table>
<thead>
<tr>
<th>Design Forces and Designations</th>
<th>Barrier Height (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>36</td>
</tr>
<tr>
<td>$F_t$ Lateral (kip)</td>
<td>67.2</td>
</tr>
<tr>
<td>$F_L$ Long. (kip)</td>
<td>21.6</td>
</tr>
<tr>
<td>$F_v$ Vertical (kip)</td>
<td>37.8</td>
</tr>
<tr>
<td>$L_t$ and $L_L$ (ft)</td>
<td>4</td>
</tr>
<tr>
<td>$H_e$ (in.)</td>
<td>25.1</td>
</tr>
</tbody>
</table>

$L_t$ = longitudinal distribution of $F_t$

$H_e$ = vertical resultant height of $F_t$
Background

• AASHTO T-7 is not ready to accept the proposed TTI TL-4 loads due to some uncertainties.

• Several issues need to be resolved:
  • TTI rigid barrier assumption – may overestimate peak dynamic loads.
  • Need independent verifications.
  • Existing yield line approach in LRFD may underestimate the actual barrier capacity.
RC Technology Deployment Project

• TD project on “Validation of bridge railing loads under MASH” is recently completed.

• Address some of the pending issues thru FEA simulations on deformable barrier models:
  • Investigation of Demand on TL-4 Concrete Barriers
  • Investigation of Capacity of TL-4 Concrete Barriers
  • New performance approach to design of new barriers
  • Effects of TL-4 Barrier Impacts on Rebar Configurations in the Deck
Investigation of Demand on TL-4 Concrete Barriers

- TL-4 barrier impact setup in LS-DYNA
## Investigation of Demand on TL-4 Concrete Barriers

### Truck Model Modifications

<table>
<thead>
<tr>
<th></th>
<th>MASH TL-4</th>
<th>Test 420020-9b (Sheikh et al. 2012)</th>
<th>Modified single-unit truck model used in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight (lb)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curb</td>
<td>13,200±2,200</td>
<td>12,400</td>
<td>12,222</td>
</tr>
<tr>
<td>Ballast</td>
<td>As Needed</td>
<td>9,750</td>
<td>9,890</td>
</tr>
<tr>
<td>Test Inertial</td>
<td>22,000</td>
<td>22,150</td>
<td>22,112</td>
</tr>
<tr>
<td><strong>Dimension (in)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheelbase (max)</td>
<td>240</td>
<td>188</td>
<td>208</td>
</tr>
<tr>
<td>Overall Length (max)</td>
<td>390</td>
<td>274</td>
<td>337</td>
</tr>
<tr>
<td>Trailer Overhang</td>
<td>N/A</td>
<td>56.0</td>
<td>89.9</td>
</tr>
<tr>
<td>Cargo Bed Height (above ground)</td>
<td>51±2</td>
<td>N/A</td>
<td>47.2</td>
</tr>
<tr>
<td><strong>Center of Mass Height (in)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballast (above ground)</td>
<td>63±2</td>
<td>N/A</td>
<td>60.2</td>
</tr>
<tr>
<td>Test Inertial (above ground)</td>
<td>N/A</td>
<td>N/A</td>
<td>51.2</td>
</tr>
</tbody>
</table>
Investigation of Demand on TL-4 Concrete Barriers

Boundary Condition of the Deck

- Truck Impact
- Fix the nodes where the stems are located

Dimensions:
- 36 in height
- 8 in width
- 30 in length
Investigation of Demand on TL-4 Concrete Barriers

Single-slope barrier testing (36 in)

- Impact Process Comparison

Main impact duration: 1 sec.

TTI Testing

LS-DYNA Simulation
Investigation of Demand on TL-4 Concrete Barriers

Single-slope barrier testing (36 in)

- Impact Process Comparison
Investigation of Demand on TL-4 Concrete Barriers

Comparison of Accelerations

- Acceleration of the truck at the center of gravity during the impact
Investigation of Demand on TL-4 Concrete Barriers

Concrete Barrier Results

- Damage comparison between the test and simulations
Investigation of Demand on TL-4 Concrete Barriers

**SAE filter versus 50-ms average**

*Ex. Force time history for MASH truck (56 mph, 11 tons)*

SAE filter doesn’t change the dynamic characteristics of impact force time history.
Investigation of Demand on TL-4 Concrete Barriers

- Effect of the truck velocity (SAE filter)

**Force time-histories of 8.8-ton truck with various speeds**
Investigation of Demand on TL-4 Concrete Barriers

- **Effect of the truck weight (SAE filter)**

The second peak increases as the weight increases.

*Force time-histories of 60-mph truck with various weights*
Investigation of Demand on TL-4 Concrete Barriers

• Equation of the dynamic peak force (SAE filter)

\[ F = 0.30V^{1.24}W^{0.41} \]

*F*: Peak force (kips)
*V*: Velocity (mph)
*W*: Truck weight (ton)

15 cases
- Velocity: 30, 40, 50, 60, 70 mph
- Weight: 8.8, 11.0, 13.2 ton

Such model will give bridge owners a framework to design barriers based on design truck loading instead of a prescribed load.
Investigation of Capacity of TL-4 Concrete Barriers

- Current approach: Yield line theory (AASHTO)
  - Conflict with load calculations (rigid barrier)
  - Simplified yielding-line pattern

- New approach
  - Similar to the “pushover curve” in earthquake engineering
  - Load versus deformation curve.
Investigation of Capacity of TL-4 Concrete Barriers

- Pushover analysis setup in LS-DYNA
Investigation of Capacity of TL-4 Concrete Barriers

- Pushover analysis of a barrier wall

![Graph showing pushover analysis with force on the y-axis and displacement on the x-axis. The graph reaches a peak at 70 kips, labeled as '70 kips. AASHTO (V shape).']

\[ R_w = \left( \frac{2}{2L_c - L_t} \right) \left( 8M_b + 8M_w + \frac{M_c L_c^2}{H} \right) \]
• Damage mode of the barrier from pushover simulation

W-shape
Investigation of Capacity of TL-4 Concrete Barriers

- Pushover analysis of a barrier wall at the end region

![Graph showing pushover analysis of a barrier wall](image)

**Figure CA13.3.1-2—Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment**

AASHTO (V shape)
Investigation of Capacity of TL-4 Concrete Barriers

• Damage mode of the barrier at an end region from pushover simulation

Yield line pattern: W-shape (half)
Investigation of Capacity of TL-4 Concrete Barriers

- $R_w$ and $L_c$ using W-shape damage mode

$$R_w = \frac{2M_{w1}}{H_1} + 6M_{c1} + \frac{M_{c1}l_t}{H_1}$$

$$L_c = 4H_1 + l_t$$

$H_1$ = height of wall (ft)

$L_c$ = critical length of yield line failure pattern (ft)

$l_t$ = longitudinal length of distribution of impact force $F_t$ (ft)

$R_w$ = total transverse resistance of the railing (kips)

$M_{c1}$ = flexural resistance of cantilevered walls about an axis parallel to the longitudinal axis of the bridge (kip-ft/ft)

$M_{w1}$ = flexural resistance of the wall about its vertical axis (kip-ft)
Investigation of Capacity of TL-4 Concrete Barriers

- Comparison between W-shape and AASHTO YLM

![Graph showing comparison between W-shape and AASHTO YLM](image-url)
Investigation of Capacity of TL-4 Concrete Barriers

- $R_w$ and $L_c$ using W-shape damage mode for the end region

\[ R_w = \frac{M_{w1}}{H_1} + 3M_{c1} + \frac{M_{c1}l_t}{H_1} \]

\[ L_c = 2H_1 + l_t \]

- $H_1$ = height of wall (ft)
- $L_c$ = critical length of yield line failure pattern (ft)
- $l_t$ = longitudinal length of distribution of impact force $F_t$ (ft)
- $R_w$ = total transverse resistance of the railing (kips)
- $M_{c1}$ = flexural resistance of cantilevered walls about an axis parallel to the longitudinal axis of the bridge (kip-ft/ft)
- $M_{w1}$ = flexural resistance of the wall about its vertical axis (kip-ft)
Investigation of Capacity of TL-4 Concrete Barriers

- Comparison between W-shape and AASHTO YLM (End region)
Investigation of Capacity of TL-4 Concrete Barriers

Yield line pattern

- In general, the AASHTO prescribes a yield-line pattern that has a “V shape” while the pushover analysis shows a “W-shaped” pattern.
- The damage pattern assumed in AASHTO ignores the horizontal yield line that could occur at the interface of the barrier, which is clearly observed in the pushover analysis.
- A vertical yield line is assumed in AASHTO (2012) on the back face of the barrier. This is different than two sloping yield lines observed in damage modes obtained by pushover simulation in LS-DYNA.
Investigation of Capacity of TL-4 Concrete Barriers

Literature Review

- Damage mode of barrier

Yield line patterns of the concrete barrier under quasi-static loading (Jeon et al. 2011)
Investigation of Capacity of TL-4 Concrete Barriers

**Literature Review**

- Damage mode of barrier

*Yield line patterns of the concrete barrier under pendulum-impact loading (Ahmed et al. 2013).*
Investigation of Capacity of TL-4 Concrete Barriers

Literature Review

- Damage mode of barrier

Yield line patterns of the concrete barrier under quasi-static loading (Namy et al. 2015).

Cracks in the front face
Investigation of Capacity of TL-4 Concrete Barriers

**Literature Review**

- **Failure mode**

  Abu-Odeh (2008): Bogie impact 20 mph, 5,000 lb

  Low-speed impact: 10 mph
Investigation of Capacity of TL-4 Concrete Barriers

Literature Review

- Damage mode of barrier

Yield line patterns of the concrete barrier under truck impact loading (Sennah and Khederzadeh 2014).
Lateral deformation of the barrier versus D/C ratio

- Dynamic demand/Capacity (D/C)

D is the dynamic impact force estimated by the demand equation. \[ F = 0.30V^{1.24}W^{0.41} \]

C is the barrier capacity based on the pushover curve.
Performance-based design

**Illustration**

- MASH TL-4 ($W = 11$ tons, $V = 56$ mph)

\[ F = 0.30V^{1.24}W^{0.41} \]

\[ F = 0.30 \times 56^{1.24}11^{0.41} = 118\text{kips} \]

<table>
<thead>
<tr>
<th></th>
<th>No damage</th>
<th>Minor damage</th>
<th>Fully-developed yielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity at yield</td>
<td>$118/0.6 = 196\text{kips}$</td>
<td>$118\text{kips}$</td>
<td>$118/1.5 = 78\text{kips}$</td>
</tr>
<tr>
<td>Peak dynamic force (MASH)</td>
<td>$118\text{kips}$</td>
<td>$118\text{kips}$</td>
<td>$118\text{kips}$</td>
</tr>
<tr>
<td>Expected deformation</td>
<td>[0.0 in, 0.1 in]</td>
<td>[0.1 in, 0.5 in]</td>
<td>[0.5 in, 2.0 in]</td>
</tr>
</tbody>
</table>
Bridge Railing-Overhang Design

- LRFD Bridge Design Manual (MnDOT 2017)

The collision force is applied to a length of barrier 3.5 feet long. Computations for the standard F-rail (see Table 13.2.4.1 in this manual) indicate that 10.2 feet of barrier length \( L_c \) is engaged in resisting the collision force in the “interior” regions. Assume that a deck width of 10.2 feet plus two barrier heights (using a 45 degree distribution) resists the tension force and overturning moment.

\[
F_{c(\text{linear})} = \frac{F_{\text{collision}}}{\text{effective deck width}}
\]

\[
= \frac{F_{\text{collision}}}{L_c + L_{45\text{deg}}} = \frac{72}{10.2 + 2.83 \cdot 2} = 4.54 \text{ kips/ft}
\]

\[
M_c = F_{c(\text{linear})} \cdot \text{(moment arm)} = 4.54 \cdot 3.22 = 14.62 \text{ kip-ft/ft}
\]

**Extreme Event II Limit State Bending Moment**

Dead Load Moment:

\[
M = (M_{\text{deck}} + M_{\text{barrier}}) = (0.15 + 0.44) = 0.59 \text{ kip-ft/ft}
\]

The moment distribution is assumed to be the same as that for the force. Is this correct?
Bridge Railing-Overhang Design

- Distribution of axial force and moment based on pushover analysis
Bridge Railing-Overhang Design

- Distribution of axial force and moment in the overhang based on pushover analysis

Force distribution length: 20 ft
Moment distribution length: 40 ft
(when barrier reaches its ultimate capacity)
## Bridge Railing-Overhang Design

### V-shape versus W-shape YLM

34in-F shape barrier (MnDOT)

<table>
<thead>
<tr>
<th></th>
<th>Collision force, 4/3*F&lt;sub&gt;t&lt;/sub&gt; (kips)</th>
<th>Barrier capacity, R&lt;sub&gt;w&lt;/sub&gt; (kips)</th>
<th>Yield line length, L&lt;sub&gt;c&lt;/sub&gt; (ft)</th>
<th>Distribution length, (L&lt;sub&gt;c&lt;/sub&gt; + 2H) (ft)</th>
<th>Uniform tensile force using 4/3*F&lt;sub&gt;t&lt;/sub&gt; (kips/ft)</th>
<th>Design moment Mc (kips-ft/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-shape YLM (AASHTO)</td>
<td>72.00</td>
<td>122.00 (reported)</td>
<td>10.20</td>
<td>15.86</td>
<td>4.54</td>
<td>14.62</td>
</tr>
<tr>
<td>W-shape YLM</td>
<td>72.00</td>
<td>130.00</td>
<td>14.83</td>
<td>20.49</td>
<td>3.51</td>
<td>11.30</td>
</tr>
</tbody>
</table>

![Diagram showing YLM design elements](image)
### Bridge Railing-Overhang Design

- **V-shape versus W-shape YLM**

36in-single slope barrier (TTI)

<table>
<thead>
<tr>
<th></th>
<th>Collision force, $4/3*F_t$ (kips)</th>
<th>Barrier capacity, $R_w$ (kips)</th>
<th>Yield line length, $L_c$ (ft)</th>
<th>Distribution length, $(L_c + 2H)$ (ft)</th>
<th>Uniform tensile force using $4/3*F_t$ (kips/ft)</th>
<th>Design moment $M_c$ (kips-ft/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-shape YLM (AASHTO)</td>
<td>72.00</td>
<td>82.73</td>
<td>8.90</td>
<td>14.91</td>
<td>4.83</td>
<td>16.08</td>
</tr>
<tr>
<td>W-shape YLM</td>
<td>72.00</td>
<td>118.43</td>
<td>15.50</td>
<td>21.50</td>
<td>3.35</td>
<td>11.16</td>
</tr>
</tbody>
</table>

*Close to the 20’ based on pushover analysis*
Preliminary Investigation of Demand on TL-5 Concrete

Velocity: 30 mph, 50 mph, and 70 mph
Weight: 60,000 lb and 80,000 lb
(# Elements: 1 million)
Preliminary Investigation of Demand of TL-5 Concrete

- **Weight:** 80,000 lb, **Speed:** 70 mph

![Force time history graph](graph.png)

- (a) Tractor impact
- (b) Impact of the rear tractor tandem axles
- (c) Impact of the rear trailer wheel
Preliminary Investigation of Demand of TL-5 Concrete

- **Force Time Histories of TL-5 Barrier Impact**

![Graph showing force time histories for 50 mph and 30 mph impacts.]

- **50 mph**
  - Force: 275 kips (Weight: 80 kips)
  - Force: 250 kips (Weight: 60 kips)

- **30 mph**
  - Force: 60 kips (Weight: 80 kips)
  - Force: 55 kips (Weight: 60 kips)
Preliminary Investigation of Demand of TL-5 Concrete

- **TL-5 Peak Impact Force**
  - 80,000 lb Tractor-semitrailer
Conclusion

- A single-unit truck model was modified to match MASH TL-4 requirements.
- A demand equation of TL-4 barrier has been proposed to quantify the peak impact load as a function of truck weight and speed.
- Capacity of the barrier has been investigated through pushover analysis. The “V-shaped” yield pattern specified in AASHTO specifications is not accurate and may be significantly underestimating the capacity of the barrier. A more accurate yield line pattern is W-shaped that also included a yield line at the interface between the barrier and deck.
- In order to relate demand to capacity, performance-based design method has been proposed. The framework is based on demand to capacity ratios for given displacement levels.
- Calculation of the overhang moment using force distribution may not be appropriate and may lead to conservative design.
Future Work for Pooled Funds Considerations

- Performance based approach for overhang design of barriers
- Experimental verification of barrier performance and damage modes for evaluating the yield line method.
- Capacity behavior / demand model for TL-5 barriers.
- TL-6 Barriers: demand model, capacity and performance verification.
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