Closing the plausibility gap: A case study

Peter Shaw | AECOM
Rob Heywood | Department of Transport and Main Roads (Engineering and Technology, Structures)
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>HML</td>
<td>Higher Mass Limits</td>
</tr>
<tr>
<td>IRI</td>
<td>International Roughness Index</td>
</tr>
<tr>
<td>COL</td>
<td>Centre of Lane</td>
</tr>
<tr>
<td>RT2H(13)</td>
<td>HML Type 2 road train as per Transport and Main Roads’ “Guideline for multi-combination vehicles”, 2013</td>
</tr>
<tr>
<td>LLF</td>
<td>Live Load Factor</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-destructive testing</td>
</tr>
<tr>
<td>UPV</td>
<td>Ultrasonic pulse velocity</td>
</tr>
<tr>
<td>CHBDC</td>
<td>Canadian Highway Bridges Design Code</td>
</tr>
<tr>
<td>PSC</td>
<td>Prestressed concrete</td>
</tr>
<tr>
<td>ERT</td>
<td>Equivalence Ratio Traffic</td>
</tr>
<tr>
<td>WiM</td>
<td>Weigh-in-motion</td>
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</table>
## Case study – Bridge description

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route type</td>
<td>Type 2 road train</td>
</tr>
<tr>
<td>Loading level</td>
<td>HML</td>
</tr>
<tr>
<td>Design loading</td>
<td>H20S16</td>
</tr>
<tr>
<td>Year of construction</td>
<td>1970</td>
</tr>
<tr>
<td>Span lengths</td>
<td>21.18 m (76 ft)</td>
</tr>
<tr>
<td>Width</td>
<td>8.53 m (28 ft)</td>
</tr>
<tr>
<td></td>
<td>2 lanes + 900 mm shoulders</td>
</tr>
<tr>
<td>Superstructure</td>
<td>4 precast pre-tensioned concrete girders @ 2.44 m centres</td>
</tr>
<tr>
<td></td>
<td>Composite reinforce concrete slab</td>
</tr>
<tr>
<td></td>
<td>Reinforced concrete diaphragms</td>
</tr>
<tr>
<td>Piers</td>
<td>Reinforced concrete</td>
</tr>
<tr>
<td></td>
<td>Single column with cantilevered headstocks</td>
</tr>
</tbody>
</table>
Assessment focus

• Initial assessments (Tiers 1 and 2)
  - Further investigation warranted

• Substructure
  - Pier headstock cantilever bending

• Superstructure
  - Shear and bending in edge girders
  - Shear and bending in internal girders.
Bridge condition

• Substructure
  - Cracking in some headstocks
  - Elastomeric bearings

• Superstructure
  - Girders generally uncracked
  - Deck slab generally sound
  - No deck wearing surface.
Bridge condition (roughness)

IRI = 3.5 to 5 m/km
Drivelines

Closing the Plausibility Gap: A Case Study
Drivelines (observations)

• Heavy vehicles generally operate in lane
  – ≈1% outside lane
  – <<1% near kerb

• Lane closures
  • Kerb
  • Slow

• Drivers advised not prepared to drive road trains at speed adjacent to kerb on this bridge.
Live Load Factor: Shoulders

- Kerb line
- Edge line
- 2.0 m
- 0.8
- 1.0
- 2.0 m

Live Load Factor
A-triple test results

- A-triple (Air), edge line, walking speed.
A-triple: Static girder strains

- Edge girders sensitive to driveline
- Inner girders insensitive to driveline.
Dynamic Increment (DI)

\[
\text{DI} = \frac{\text{Peak dynamic response} - \text{Peak static response}}{\text{Peak static response}}
\]

- Engineering objective is to estimate the peak static + dynamic response from peak static response.
- Calculated for elements directly loaded by truck.
- High DIs in lightly loaded elements generally not relevant.

(Cantieni, 1983; Cantieni et al, 2000)
# A-triple: Dynamic Increment

- $\text{DI} < \text{DLA} = 0.4$
- $\text{DI}_{\text{air}} < \text{DI}_{\text{steel}}$
- $\text{DI}_{\text{super}} \leq 0.2$
- $\text{DI}_{\text{sub}} \leq 0.3$
- $\text{DI}_{\text{sub}} > \text{DI}_{\text{girder}}$
- $\text{Peak Dyn Eff}_{\text{HML}(\text{air})} \approx 1.03 \text{ Peak Dyn Eff}_{\text{GML}(\text{steel})}$

<table>
<thead>
<tr>
<th>Description</th>
<th>All</th>
<th>Pier strains (Air)</th>
<th>Pier strains (Steel)</th>
<th>Girder strains (Air)</th>
<th>Girder strains (Steel)</th>
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<tbody>
<tr>
<td>Average DI</td>
<td>0.12</td>
<td>0.13</td>
<td>0.23</td>
<td>0.02</td>
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<tr>
<td>Maximum DI</td>
<td>0.31</td>
<td>0.20</td>
<td>0.31</td>
<td>0.07</td>
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In-service monitoring

- Scatter plot – extreme 0.5 day girder strain.
In-service monitoring (cont.)

- Event A – Road Train

![Graph showing strain over time for different sensors](image)

- "MS_CSG_1" ("micro strain")
- "MS_CSG_2" ("micro strain")
- "MS_CSG_3" ("micro strain")
- "MS_CSG_4" ("micro strain")
In-service monitoring (cont.)

- Event E – Crane
In-service monitoring (cont.)

- Event J – Load Platform
In-service monitoring (edge girder)
In-service monitoring (inner girder)
Monitoring Live Load Model

- RT2H(13)
  - Centre of lane
    - Dynamic Load Allowance (DLA)
      - Super = 0.2
      - Sub = 0.3
    - $LLF_{COL} = 1.8$
  - Kerb
    - DLA
      - Super = 0.2
    - $LLF_{Kerb} = 1.15$ << reduced LLF for operating on shoulder
Monitoring Live Load Model (cont.)

- Dynamic increment
  - IRI 3.5 to 5 m/km
  - $D_{\text{super}} \leq 0.2$ \hspace{0.5cm} < 0.4
  - $D_{\text{sub}} \leq 0.3$
  - $D_{\text{air}} < D_{\text{steel}}$
  - $D_{\text{sub}} > D_{\text{super}}$

- Heavy vehicles generally operate in lane (≈99%)
  - Kerb drivelines are uncommon
  - Influenced by lane closures (slow).
Concrete strength – Core testing
Cores: Compression strength

- **ACI / AS 3600**
- **MRTS 70**
- **NZ BM (n=29, COV = 4.5%)**
- **CHBDC (n=29, COV = 4.5%)**
- **CHBDC max for shear benefit**
- **\( f_{c,\text{assessment}} \) (hypothesis)**
- **\( f_{c,\text{design}} \)**

**Closure**

100 mm cores: 22
150 mm cores: 7
Total: 29

- **Average of \( f_c \) transfer**
- **Average of \( f_{c,28d} \)**
- **Min of \( f_{core,46y} \)**
- **Average of \( f_{core,46y} \)**
- **Max of \( f_{core,46y} \)**
- **StdDev of \( f_{core,46y} \)**
Stub versus girders?

NDT assessment for concrete strength - Q Value and UPV

Rebound Hammer (Q, %)

Ultrasonic Pulse Velocity (V, m/s)

S3 - G1  S3 - G2  S3 - G3  S3 - G4  S21 - G1  S21 - G2  S21 - G3  S21 - G4  Stub  Cores

Q(average)  V(average)
Concrete strength

• Transport and Main Roads Test
  - One girder 29 samples
  - $f_{\text{core}}$ 46 years average 90 MPa > 2$f_c$ 28 days
  - $f_{\text{core}}$ 46 years assessment > 65 MPa (CHBDC)

• Minnesota Department of Transport
  - One girder
  - $f_{\text{core}}$ aged average 68 MPa ~ 1.7$f_c$ 28 days

• Ductility
  - Increased minimum shear reinforcement for higher strength
  - System factor if $A_{sv} < A_{sv,\text{min}}$ for higher strength.
Destructive tests on PSC Girder

- Initial shear cracking

Runzell, Shield and French, “Shear Capacity of Prestressed Concrete Beams”, Minnesota DOT Report MN/RC 2007-47, Figure 6.2
Destructive tests on PSC Girder (cont.)

Runzell, Shield and French, “Shear Capacity of Prestressed Concrete Beams”, Minnesota DOT Report MN/RC 2007-47, Figure 6.3
Theoretical assessment
Grillage model

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Modelling

- Superstructure grillage
  - Spring supports

- Shear forces in girder
  - Spacing of transverse members near supports
  - Wheel loads
    - Concentrated point load
    - Many concentrated point loads
  - Applied to transverse members
  - Diaphragms

- Torsional constants
  - Cracked versus uncracked

- Calibration against experimental data.
Support stiffness

- Bearing stiffness
- Cantilever stiffness
- Elastic
  - Not significant
- Plastic deformation of headstock
  - Significant.
Location of critical section ($M_{hog}$)

- **AS 5100.5 – 2004 Cl 7.2.10**
  - Minimum of:
    - 0.15 x column width
    - 0.50 x overall depth
- Significant increase in $M_{hog}$, especially for wide columns
- Design provision
- Not appropriate for bridge assessment.
Location of critical section ($M_{hog}$)

- AS 5100.5 Strut-tie
  - Calculate max tension in tie
- Beam analogy
  - Shear force diagram
  - Moment diagram
  - Max moment occurs when shear force is zero
  - $x =$ the distance from the face for column to resist $P^*$
  - $x = f(P^*, \text{dimensions}, f'_c)$
  - $M_{hog} =$ area under shear force diagram
  - $M_{hog} = P(L_c + x/2)$ for rect col.
Headstock cantilever

- Side face reinforcement contribution can be significant
- Shear
  - Strut-tie
- Deck diaphragms at pier
  - Acts in parallel
  - Attracts load once headstock cantilever has yielded
  - Stability limited by mass of deck
  - Redundancy
  - Warning.
Headstock assessment

- **Inventory Level**
  - Centre of lane: ERT > 1
  - Edge of lane / kerb: ERT < 1

- **Operational Level**
  - ERT > 1
    - LLF
      - Monitoring
    - WiM
    - Drive-line
      - Monitoring
    - Measured DLA
  - Structure Management Plan.

<table>
<thead>
<tr>
<th>Driveline Scenario</th>
<th>ERT (LLF = 2.0, DLA = 0.4)</th>
<th>LLF(1+DLA) Required for ERT = 1.0</th>
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</thead>
<tbody>
<tr>
<td>Kerb</td>
<td>0.77</td>
<td>2.16</td>
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<tr>
<td>Edge line</td>
<td>0.86</td>
<td>2.41</td>
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<tr>
<td>Centre of lane</td>
<td>1.04</td>
<td>&gt;2.80</td>
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</tbody>
</table>
PSC girder: Shear assessment

- Inventory assessments low
- Critical sections for shear > d from support.
Shear assessment

- Peak shear forces present for short periods
- Accompanying Vehicle Factors?
- Static + dynamic response?
- Concrete properties – loading rate?
Shear strength: Effect of $f'_c$

- Shear strength increases with concrete strength to a limit – no significant increase for $f'_c > 65$ MPa (CHBDC)
- Concrete core strength: $f'_{c, aged} > 65$ Mpa.
## Edge girder shear assessment

<table>
<thead>
<tr>
<th>Scenario</th>
<th>T31</th>
<th>T32</th>
<th>T33</th>
<th>T36</th>
<th>T36</th>
<th>T38</th>
<th>T38</th>
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</thead>
<tbody>
<tr>
<td>RV</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
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<td>T1</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
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<tr>
<td>$f'_c$</td>
<td>38</td>
<td>38</td>
<td>38</td>
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<td>38</td>
<td>55</td>
<td>55*</td>
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<td>LLF</td>
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<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>DLA</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>AVF</td>
<td>0.8</td>
<td>0.8</td>
<td>0.0</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8*</td>
</tr>
<tr>
<td>Drive-line</td>
<td>Kerb</td>
<td>Kerb</td>
<td>Kerb</td>
<td>Kerb</td>
<td>COL</td>
<td>Kerb</td>
<td>All*</td>
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<tr>
<td>$ERT_{Edge}$</td>
<td>0.59</td>
<td>0.69</td>
<td>0.72</td>
<td>0.81</td>
<td>&gt;1</td>
<td>0.92</td>
<td>&gt;1</td>
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</tbody>
</table>
Edge girder shear assessment (cont.)

- Accompanying Vehicle Factor – no significant benefit
- ERT > 1 if:
  - Material factors, DLA, Driveline or
  - Material factors, LLF, DLA, concrete strength
- A few options to explain plausibility gap.
### Inner girder shear assessment

<table>
<thead>
<tr>
<th>Scenario</th>
<th>T31</th>
<th>T31</th>
<th>T31</th>
<th>T32</th>
<th>T36</th>
<th>T37</th>
<th>T38</th>
<th>T38</th>
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<tbody>
<tr>
<td>RV</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
<td>6H</td>
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<tr>
<td>Material factors</td>
<td>T1</td>
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<td>T1</td>
<td>T1</td>
<td>C</td>
<td>C</td>
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<td>$f'_c$</td>
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<td>55*</td>
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<td>LLF</td>
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<td>DLA</td>
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<td>0.8</td>
<td>0.8</td>
<td>0.0</td>
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</tr>
<tr>
<td>Drive-line</td>
<td>Kerb</td>
<td>Edge</td>
<td>COL</td>
<td>COL</td>
<td>COL</td>
<td>COL</td>
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<td>ERT$_{Inner}$</td>
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<td>0.61</td>
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<td>0.69</td>
<td>0.81</td>
<td>&gt;1</td>
<td>0.93</td>
<td>&gt;1</td>
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</table>
Inner girder assessment

• Driveline – no significant benefit
• ERT > 1 if:
  ▪ Material Factors, LLF, DLA, concrete strength
• Accompanying vehicle model
  ▪ what is reasonable?
• Increased concrete strength?
  ▪ Is the observed increase likely elsewhere?
Discussion

• Assessments sensitive to assumptions
• If all Operational Parameters acceptable “plausibility gap” is explained
  - Is this reasonable?
  - Too risky?
  - Swiss cheese?
• If Operational Parameters not acceptable then load limit is less than a semi-trailer
  - Not credible.
What would Operational Parameters mean for Priority Bridges?

- Sample of 86 Priority Bridges
  - Steel and concrete bridges
  - Superstructures
    - Prestressed concrete girders
    - Steel girders
    - Deck units
  - Substructures
    - Portal frames with and without cantilevers
    - Single columns with cantilevered headstocks
    - Others
- Sanity check / calibration
  - How far is reasonable?
### Sensitivity of Priority Bridges to Individual Operational Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
<th>Value 6</th>
<th>Value 7</th>
<th>Value 8</th>
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<td>$f_{c,\text{increase}}/f_c$</td>
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<td>1.25</td>
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<td>1.5</td>
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<td>LLF* = Min(2.3-0.016Span) &gt; 1.65</td>
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<td>Route MCV</td>
<td>Route MCV</td>
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<td>Route MCV</td>
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Sensitivity of Priority Bridges to combinations of Operational Parameters
Sensitivity of Priority Bridges to combinations of Operational Parameters
Possible management strategies

• Inventory assessment
  - Access restrictions for freight vehicles and permit vehicles
    ▪ Unpalatable
  - Strengthening / replacement
    ▪ Unaffordable

• Operational assessment (risk-informed)
  - Structure Management Plans
  - Driveline
  - WiM
  - Revised inspection regime and monitoring
  - Materials testing
  - Access management
  - Potential reduced life

• Enforcement of mass and dimension.
Conclusions

• Bridge Assessment ≠ Bridge Design in Reverse
• Closing the plausibility gap essential
  - Careful analysis
  - Review of assumptions
  - Multiple factors contribute.
Conclusions

• Operational / Risk informed approach
  - Allows bridges to remain in service longer
  - Possible reduction in remaining life
  - Network and bridge specific parameters
  - Are the increased risks acceptable?
  - Structure Management Plans

• Reasonable or too risky?
  - How far?
Thank you