WIM-BASED FATIGUE DAMAGE ASSESSMENT

TRANSPORTATION RESEARCH BOARD 2020

Lectern Session 1303 - Effects of Fatigue and Corrosion on Steel Girder Bridges

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DATA PROCESSING,
ANALYSIS AND
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RESULTS.
INTRODUCTION

ACCORDING TO ASCE INFRASTRUCTURE CARD (2017):

- 4 out of 10 bridges are 50 years or older (avg. age 43 years).
- 25% (151,845) bridges are structurally or functionally deficient.
- 188 million trips through structurally deficient bridges daily.
- About 60,000 bridges (10 percent) are posted for a weight or speed limit.
- A percentage of structurally deficient (SD) bridges reduced from 12.5 to 9% over the last decade due to a number of newly built or replaced bridges.
- Failures due to overload or deterioration are strongly age related.

INTRODUCTION

TRAFFIC DATA

- As of 2011 over 700 portable and permanent WIM stations are currently in operation around the country (Ghosn et al. 2011).

- As of now traffic data recorded by 1124 WIM stations during recent 10 years from 44 States is available.

- The magnitude of traffic loads is controlled by:
  - Legal load limits
  - Permit load and number
  - Control of illegally overloaded vehicles.

AASHTO LRFD Bridge design specifications:

- The stress range calculated for a code-specified fatigue design truck is limited to avoid fatigue cracking caused by the accumulation of damage from repetitive truck loading.
- The AASHTO fatigue design truck is intended to represent truck traffic.
- Steel bridges are more prone to fatigue cracking compared to other types of bridges.
- Passage of each heavy truck uses a tiny amount of the fatigue life of a bridge.

Stages of Fatigue Process:

1. Initiation of cracks
2. Propagation of cracks
3. Fracture
SUMMARY OF RELEVANT STUDIES ON ESTIMATED COST OF DAMAGE DUE TO OVERWEIGHT TRAFFIC

The study of the impacts of vehicular traffic on infrastructure has been conducted in many states. Some of the states have sponsored research for an experimental approach and some for analytical studies.

<table>
<thead>
<tr>
<th>Source</th>
<th>State</th>
<th>Transportation infrastructure</th>
<th>Mechanisms considered</th>
<th>Dataset – Load side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oversize/Overweight Vehicle Permit Fee Study</td>
<td>Texas</td>
<td>Pavement</td>
<td>Rutting, fatigue cracking, and roughness</td>
<td>OS/OW issued permits</td>
</tr>
<tr>
<td>Oversize/Overweight Vehicle Permit Fee Study</td>
<td>Texas</td>
<td>Bridge</td>
<td>Fatigue and different fatigue curves depending upon type of material</td>
<td>1. OS/OW issued permits 2. Non-routed permits</td>
</tr>
<tr>
<td>Effects of Overweight Vehicles on NYSDOT Infrastructure</td>
<td>New York State</td>
<td>Bridge</td>
<td>1. Overstress of main members 2. Cyclic fatigue accumulation in main members and decks</td>
<td>Weigh-In-Motion (WIM) data</td>
</tr>
<tr>
<td>Effects of Overweight Vehicles on NYSDOT Infrastructure</td>
<td>New York State</td>
<td>Pavements</td>
<td>Incremental cost approach</td>
<td>Weigh-In-Motion (WIM) data</td>
</tr>
<tr>
<td>Impact of Freight on Highway Infrastructure in New Jersey</td>
<td>New Jersey</td>
<td>Bridges</td>
<td>Fatigue in steel bridge girders, pre-stressed bridge girder tendons and RC decks</td>
<td>Weigh-In-Motion (WIM) data</td>
</tr>
</tbody>
</table>
FATIGUE LIFE RELATIONSHIP

\[ NS_r^m = A \]

Where:
- \( m \) – slope constant (3 for steel)
- \( S \) – nominal stress range
- \( N \) – number of cycles to failure
- \( A \) – constant for a given detail
The S-N curves were developed using constant-amplitude stress range test data. However, bridges are subjected to variable amplitude stress cycles.
TRAFFIC INDUCED FATIGUE LOADING
TRAFFIC INDUCED FATIGUE LOADING (VARIABLE AMPLITUDE)

Every passage of a truck across a bridge creates one or more stress cycles in the structural components, which results in the accumulation of fatigue damage over time.
LOADING USED IN DEVELOPING S-N CURVES (CONSTANT AMPLITUDE)

An equivalent constant amplitude stress range, commonly referred to as an effective stress range $S_{\text{eff}}$, can be calculated using the Palmgren-Miner rule.

$$S_{\text{eff}} = \left[ \sum \frac{n_i}{N} S_i^m \right]^{1/m}$$

where:
- $n_i$ – number of cycles at the $i^{th}$ stress range, $S_i$
- $N$ - total number of cycles.
CYCLE COUNTING: BENDING MOMENT TIME HISTORY

- Introduced in 1968 by Matsuishi and Endo.
- Convenient to program.
- Counts full and half cycles.
- The magnitude of cycle is calculated as a difference between “peak” and “valley”.
- Once the cycle is identified it is eliminated from the moment time history and the remaining “peaks” and “valleys” are renumbered.
The Palmgren-Miner rule provides a rational means to account for the cumulative damage from a spectrum of applied stress ranges of variable amplitude.

\[ S_{\text{eff}} = \left[ \sum \frac{n_i}{N} S_i^m \right]^{1/m} \]

where:
- \( n_i \) – number of cycles at the \( i^{\text{th}} \) stress range, \( S_i \)
- \( N \) - total number of cycles.

At a specific point along a bridge girder, the applied range of bending moment can be determined by multiplying the applied stress range by the section modulus.

\[ M_{\text{eff}} = \left[ \sum \frac{n_i}{N} M_i^m \right]^{1/m} \]

where:
- \( n_i \) – number of cycles at the \( i^{\text{th}} \) moment range, \( M_i \)
- \( N \) - total number of cycles.
Traffic in both directions of travel are combined.

Each WIM record is analyzed for 30, 60, 90, 120, and 200 ft span lengths.

Results presented are for a location 20% of the span length from the upstream support (cover plate end).

The amount of damage \( D_m \) is calculated from the effective bending moment determined from the WIM data.

\[
D_m = N M_{eff}^m
\]
Based on the study performed by Franklin, the base metal at the end of a bottom flange cover plate is considered here as the most fatigue prone detail in Alabama’s steel girder bridges.

\[ D = \frac{N * S_{eff}^3}{R_R * A} \]

\( D \) are calculated from WIM data each month for convenience, the \( D \) value for the year will be the sum of the values calculated for each month.
WIM data available from 8 WIM stations
Duration of WIM recording – year 2014

<table>
<thead>
<tr>
<th>WIM Site code</th>
<th>County</th>
<th>Number of WIM records before QC</th>
<th>Number of WIM records after QC</th>
</tr>
</thead>
<tbody>
<tr>
<td>911 (US280)</td>
<td>US280 Cosa Co.</td>
<td>1,092,751</td>
<td>357,854</td>
</tr>
<tr>
<td>931 (I65)</td>
<td>I65 Limestone Co.</td>
<td>3,655,980</td>
<td>1,584,347</td>
</tr>
<tr>
<td>933 (AL157)</td>
<td>AL157 US72 Colbert Co.</td>
<td>977,580</td>
<td>427,505</td>
</tr>
<tr>
<td>934 (US78)</td>
<td>US78 Walker Co.</td>
<td>688,388</td>
<td>169,407</td>
</tr>
<tr>
<td>942 (US231)</td>
<td>US231 Montgomery Co.</td>
<td>1,262,375</td>
<td>787,426</td>
</tr>
<tr>
<td>960 (US84)</td>
<td>US84 Clark Co.</td>
<td>521,484</td>
<td>305,566</td>
</tr>
<tr>
<td>961 (I65)</td>
<td>I65 Mobile Co.</td>
<td>2,136,008</td>
<td>851,213</td>
</tr>
<tr>
<td>964 (US231)</td>
<td>US231 Dothan Co.</td>
<td>1,217,687</td>
<td>642,337</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>11,552,253</td>
<td>5,125,655</td>
</tr>
</tbody>
</table>
SORTING ALGORITHM - TRAFFIC DATA

- Legal trucks
- Legally overloaded (vehicles operating with permits due to overload)
- Illegally overloaded (overloaded vehicles operating without permits)

<table>
<thead>
<tr>
<th>Vehicular traffic</th>
<th>Legal loads</th>
<th>Overloaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal weight limits</td>
<td>Annual permits</td>
<td>Super load permits</td>
</tr>
<tr>
<td>Grandfather provisions</td>
<td>Single trip permits</td>
<td>Illegal trucks</td>
</tr>
</tbody>
</table>
TECHNICAL APPROACH

SORTING ALGORITHM – ALABAMA TRUCK SIZE AND WEIGHT (TS&W) REGULATIONS

LEGAL LOADS

- Federal legal weight limit
  - GVW - 80 kips
  - Single axle - 20 kips
  - Tandem axle - 34 kips
  - Federal Bridge Formula Weights

- Grandfather provisions
  - GVW - 84 kips
  - Single axle - 20 kips
  - Tandem axle - 36 kips
  - Tridem axle - 42 kips
  - Federal Bridge Formula Weights (with some exceptions)

+ 10% axle weight tolerance

ALL PERMITS

- Annual permits
  - GVW ≤ 150 kips
  - GVW > 100 kips require advance routing
  - Single axle - 22 kips
  - Tandem axle - 44 kips
  - Tridem axle - 66 kips
  - 4 axle – 88 kips
  - 5 axle – 110 kips
  - 6 axle – 122 kips
  - 7 axle – 142 kips
  - 8 axle – 150 kips

- Single trip permits
  - Vehicles exceeding annual permit limits

- Super load permits
  - GVW > 250 kips
TECHNICAL APPROACH

IDENTIFICATION OF PERMIT & ILLEGALLY OVERLOADED VEHICLES

Raw WIM Database

Decrypted in iAnalyze

Class 0 & 4-13 + QC check

Filtered WIM Database

ALDOT issued permit database

OW permits selected + errors eliminated

Data correction + Map routes using Google Maps API

Checking permit truck passing WIM station

Legal vehicles

Permit / Illegally overloaded

Permit records passing WIM station

Permit records in WIM Database

Permit records NOT passing WIM station

Illegal vehicles in WIM Database

Records are matched based on date of travel, WIM station and vehicle configuration
GIS ROUTING PROCEDURE

OW PERMIT TRUCKS - 2014

Credits: Jacek Chmielewski, Ph.D.
COMPARISON OF WIM SITE-SPECIFIC DAMAGE

ACCUMULATED DAMAGE, DM AT THE UPSTREAM COVER PLATE END

<table>
<thead>
<tr>
<th>Site</th>
<th>30 ft</th>
<th>60 ft</th>
<th>90 ft</th>
<th>120 ft</th>
<th>200 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 911</td>
<td>0.001</td>
<td>0.010</td>
<td>0.059</td>
<td>0.198</td>
<td>1.378</td>
</tr>
<tr>
<td>Site 931</td>
<td>0.006</td>
<td>0.079</td>
<td>0.458</td>
<td>1.614</td>
<td>11.686</td>
</tr>
<tr>
<td>Site 933</td>
<td>0.001</td>
<td>0.016</td>
<td>0.094</td>
<td>0.309</td>
<td>2.088</td>
</tr>
<tr>
<td>Site 934</td>
<td>0.000</td>
<td>0.006</td>
<td>0.031</td>
<td>0.093</td>
<td>0.579</td>
</tr>
<tr>
<td>Site 942</td>
<td>0.002</td>
<td>0.024</td>
<td>0.145</td>
<td>0.493</td>
<td>3.447</td>
</tr>
<tr>
<td>Site 960</td>
<td>0.001</td>
<td>0.012</td>
<td>0.075</td>
<td>0.250</td>
<td>1.678</td>
</tr>
<tr>
<td>Site 961</td>
<td>0.003</td>
<td>0.038</td>
<td>0.228</td>
<td>0.782</td>
<td>5.507</td>
</tr>
<tr>
<td>Site 964</td>
<td>0.002</td>
<td>0.021</td>
<td>0.125</td>
<td>0.434</td>
<td>3.100</td>
</tr>
</tbody>
</table>
### Comparison of WIM Site-Specific Damage

#### Number of Records at the Upstream Cover Plate End for 200-FT Span

<table>
<thead>
<tr>
<th>Site</th>
<th>Legal Load</th>
<th>Permit Load</th>
<th>Illegal Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>911</td>
<td>334,809</td>
<td>914</td>
<td>22,131</td>
</tr>
<tr>
<td>931</td>
<td>921,334</td>
<td>161,385</td>
<td>501,628</td>
</tr>
<tr>
<td>933</td>
<td>401,926</td>
<td>391</td>
<td>25,188</td>
</tr>
<tr>
<td>934</td>
<td>148,927</td>
<td>192</td>
<td>20,288</td>
</tr>
<tr>
<td>942</td>
<td>748,425</td>
<td>1,413</td>
<td>37,588</td>
</tr>
<tr>
<td>960</td>
<td>236,972</td>
<td>4,111</td>
<td>64,483</td>
</tr>
<tr>
<td>961</td>
<td>682,211</td>
<td>19,193</td>
<td>149,809</td>
</tr>
<tr>
<td>964</td>
<td>586,321</td>
<td>2,314</td>
<td>53,702</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>200,000</td>
</tr>
<tr>
<td>400,000</td>
</tr>
<tr>
<td>600,000</td>
</tr>
<tr>
<td>800,000</td>
</tr>
<tr>
<td>1,000,000</td>
</tr>
<tr>
<td>1,200,000</td>
</tr>
<tr>
<td>1,400,000</td>
</tr>
<tr>
<td>1,600,000</td>
</tr>
</tbody>
</table>
COMPARISON OF WIM SITE-SPECIFIC DAMAGE

ACCUMULATED DAMAGE, $D_m$ AT THE UPSTREAM COVER PLATE END FOR 200-FT SPAN

Legal load:
- Site 911: 1.000
- Site 931: 3.433
- Site 933: 1.360
- Site 934: 0.356
- Site 942: 2.861
- Site 960: 0.733
- Site 961: 2.634
- Site 964: 2.350

Permit load:
- Site 911: 0.010
- Site 931: 2.195
- Site 933: 0.004
- Site 934: 0.003
- Site 942: 0.019
- Site 960: 0.054
- Site 961: 0.260
- Site 964: 0.028

Illegal load:
- Site 911: 0.368
- Site 931: 6.141
- Site 933: 0.730
- Site 934: 0.221
- Site 942: 0.567
- Site 960: 0.892
- Site 961: 2.615
- Site 964: 0.722
COMPARISON OF WIM SITE-SPECIFIC DAMAGE

NUMBER OF VEHICLES
- Legal load: 79%
- Permit load: 4%
- Illegal load: 17%

AMOUNT OF DAMAGE, $D_M$
- Legal load: 50%
- Permit load: 9%
- Illegal load: 41%
DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

SPAN 86-W OF CBD INTERCHANGE IN BIRMINGHAM, AL

Span 86-W
7 in. slab thickness
Slope = 0.066 ft/ft
Looking with traffic

North
## Damage at a Specific Fatigue Prone Detail

### Bridge Data Inputs for Span 86-W Bridge on Interstate I-59/20 in Birmingham, Alabama

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section modulus (S)</td>
<td>702 in³</td>
</tr>
<tr>
<td>Span length (L)</td>
<td>60 ft</td>
</tr>
<tr>
<td>Girder distribution factor (GDF)</td>
<td>0.51</td>
</tr>
<tr>
<td>Dynamic load allowance (IM)</td>
<td>0.15</td>
</tr>
<tr>
<td>Location of upstream cover plate end</td>
<td>11.0 ft</td>
</tr>
<tr>
<td>x/L of upstream cover plate end</td>
<td>0.2</td>
</tr>
<tr>
<td>Location of downstream cover plate end</td>
<td>53.6 ft</td>
</tr>
<tr>
<td>x/L of downstream cover plate end</td>
<td>0.8</td>
</tr>
<tr>
<td>Number of traffic lanes</td>
<td>4</td>
</tr>
<tr>
<td>Direction of traffic</td>
<td>One-direction only</td>
</tr>
<tr>
<td>Fraction of truck traffic (p)</td>
<td>0.85</td>
</tr>
<tr>
<td>Resistance factor for mean fatigue life for E' detail (R_R)</td>
<td>1.9</td>
</tr>
<tr>
<td>Ratio of measured to calculated stress range (P)</td>
<td>0.6</td>
</tr>
<tr>
<td>Average daily truck traffic (ADTT)</td>
<td>2809</td>
</tr>
<tr>
<td>Number of lanes (n_L)</td>
<td>4</td>
</tr>
</tbody>
</table>
DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

EVALUATION OF A SPECIFIC BRIDGE USING TRAFFIC DATA FROM WIM SITE 931

\[ D = \frac{p}{R_R A} * \left( \frac{GDF \cdot (1 + IM) \cdot P \cdot R_p}{S} \right)^3 * N_{M_{eff}}^3 \]

Fraction of mean fatigue life expended at the upstream cover plate end, \( D_m = 0.0099 \)

» If a bridge is designed for 75 years, then \( \frac{1}{75} = 0.0133 > 0.0099 \)
   
   Rate of damage accumulation is less than anticipated during the design.

» If there is same annual traffic on the bridge each year of its life, then its mean service life would be \( \frac{1}{D} = 101 \) years.
FRACTION OF MEAN FATIGUE LIFE EXPENDED AT A SPECIFIC FATIGUE PRONE DETAIL (DM) FOR AISI SHORT SPAN STEEL BRIDGES

AISI Short-Span Steel Bridges (American Iron and Steel Institute 1995) has real-life bridge design examples of composite rolled beams with welded cover plates.

<table>
<thead>
<tr>
<th>Span (ft)</th>
<th>Beam cross-section</th>
<th>Thickness x Width (in)</th>
<th>Location (in)</th>
<th>Girder spacing (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>W 33x118</td>
<td>3/4 x 9 -1/2</td>
<td>5.5</td>
<td>10</td>
</tr>
<tr>
<td>90</td>
<td>W 40x183</td>
<td>1-1/2 x 10</td>
<td>9.5</td>
<td>10</td>
</tr>
<tr>
<td>120</td>
<td>W 36x300</td>
<td>2 x 14</td>
<td>14.5</td>
<td>10</td>
</tr>
</tbody>
</table>

The fraction of mean fatigue life expended at a specific fatigue prone detail (Dm), was calculated for the cover plate ends (detail category Type E’) at the upstream and downstream locations for some of these example bridge designs.
DAMAGE AT A SPECIFIC FATIGUE PRONE DETAIL

FRACTION OF MEAN FATIGUE LIFE EXPENDED AT A SPECIFIC FATIGUE PRONE DETAIL (DM) FOR AISI SHORT SPAN STEEL BRIDGES

$D_m$ at upstream cover plate end (Lane 1 & 2, year 2014)
FRACTION OF MEAN FATIGUE LIFE EXPENDED AT A SPECIFIC FATIGUE PRONE DETAIL (DM) FOR AISI SHORT SPAN STEEL BRIDGES

\[ D_m \text{ at upstream cover plate end (Lane 3 & 4, year 2014)} \]
Variable data formats applicable

WIM Data format conversion

Comprehensive QC

Cumulative Nominal Damage ($D_m$) computation

To be improved to bridge specific analysis and real-time traffic data processing
**EVALUATION OF A SPECIFIC BRIDGE USING TRAFFIC DATA**

**WIM Station 931 for Year 2014**

For $L = 60$ ft and $x/L = 0.2$ (upstream coverplate end)

<table>
<thead>
<tr>
<th>Month</th>
<th>No. of records</th>
<th>$N$ (cycles)</th>
<th>$M_{eff}$ (kip-ft)</th>
<th>$D = NM_{eff}^3$ (cycles(kip-ft)$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>66423</td>
<td>145916</td>
<td>257.64</td>
<td>2.50E+12</td>
</tr>
<tr>
<td>Feb</td>
<td>62731</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>71102</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>69661</td>
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<td></td>
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<tr>
<td>May</td>
<td>73938</td>
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<tr>
<td>Jun</td>
<td>72429</td>
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<td></td>
<td></td>
<td>842972</td>
</tr>
</tbody>
</table>

**AL WIM DAI v1.0**
CONCLUSIONS

- Based on the combined WIM data, 20% of the vehicles are overloaded (both permit loads and illegal loads), and this create more than 50% of the total fatigue damage.

- The 16-18% of trucks that are illegally overloaded create more than 40% of the total damage.

- 5-axle Class 9 trucks cause more than 70% of fatigue damage.

- For traffic recorded at WIM site 931 (Athens), the fatigue life of steel girder bridges is consumed four times faster than expected for a design life of 75 years.

- **AL WIM QC** helps in timely identification of malfunctioning of WIM systems. **AL WIM DAI** provides significant information of damage accumulation on bridges.
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THANK YOU FOR YOUR ATTENTION!
QUESTIONS?
Part 2: Identification of Permit & Illegally Overloaded Vehicles

GIS routing procedure

- RAW WIM Database
  - Decrypting in iAnalyze
    - Class 0 & 4-13 + QC check
      - Filtered WIM Database

- Permit Data
  - ALDOT issued permit database
    - OW permits selected + errors eliminated
      - Map routes using Google Maps API
        - Checking permit truck passing WIM station

- Records matched based on date of travel, WIM station and vehicle configuration
  - Permit in WIM Database
  - Permit records passing WIM station
  - Permit records NOT passing WIM station
  - Illegal vehicles in WIM Database
  - Legal vehicles

Permit / Illegally overloaded

- Permit records in WIM Database
Permit Truck Routes – Year 2014

Credits: Jacek Chmielewski, Ph.D.
Part 3: Assessment of Fatigue Damage Accumulation

Traffic induced fatigue loading (variable amplitude)

Loading used in developing S-N curves (constant amplitude)
The effective stress range, $S_{eff}$, is calculated:

$$S_{eff} = \frac{M_{eff} \cdot GDF \cdot (1 + IM) \cdot P}{S}$$

where:

- $M_{eff}$ – effective moment range from WIM data
- $GDF$ – girder distribution factor for a single loaded lane
- $IM$ – dynamic load allowance
- $P$ – ratio of measured to calculated stress range
- $S$ – section modulus for the specific fatigue detail
Finite Life Check

Maximum stress range at the upstream cover plate end – E’ type detail

\[ \Delta f_{TH} = 2.6 \text{ ksi} \]

1 in 2,000 cycles

Probability

0.9999
0.999
0.99
0.95
0.9
0.75
0.5
0.25
0.1
0.05
0.0001

Stress range, ksi

60ft
90ft
120ft

0 1 2 3 4 5 6 7 8 9 10
2.6
Generic – Q4: How do the amounts of fatigue damage caused by various classes of trucks compare?

Location 911 – Top – Cover plate end