A GIS-Based Index for Estimating Road Vulnerability to Damage from Overweight Vehicles

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Introduction

• Institute for Transportation Research and Education (ITRE) supports North Carolina State Highway Patrol (NCSHP) Motor Carrier Enforcement (MCE):
  ❍ Helping to reduce Commercial Motor Vehicle (CMV) related crashes
  ❍ preserving the states road and bridge infrastructure

• End goal: enable more data driven in their enforcement efforts
Why Develop a Road Vulnerability Index (RVI)?

- MCE planner has to figure out where to send S&W troopers to check on trucks.
- Right now, He/she has to look at bridges, pavement condition, and estimated truck volume layers separately.
- RVI would give them a single simplified guide to focus enforcement resources.
RVI Model Development

- Three components currently make up Road Vulnerability Index (RVI)
  - Relative Truck Exposure Index (RTEI)
  - Pavement Condition Ratings Index (PCRI)
  - Bridge Severity Index (BSI)

$$RVI = \frac{\alpha RTEI + \beta PCRI + \gamma BSI}{\alpha + \beta + \gamma}$$
Road Vulnerability Index

- RTEI
  - Truck Count
  - Truck Capacity
- PCRI
  - Alligator Cracking
  - Rutting
- BSI
  - Bridge Rating
  - Bridge Distress
  - Posted Weight
- GIS
Relative Truck Exposure Index (RTEI)

• Measured as a ratio of Truck Count to Truck Capacity

\[ RTEI = \frac{T}{v_t} \]
Truck Count

- Point layer obtained from Traffic Survey Unit at NCDOT

- Represent limited number of traffic monitoring stations on Interstates, US & NC Highways

- Only routes with truck count included in RVI

- NCDOT hopes to tag all routes with truck count in the future
Truck Count

• Two types of truck counts
  ➡ Primary
  ➡ Secondary

• Primary route supersedes secondary route

• If multiple truck count stations for a route exist, average was taken
Truck Capacity

- Derived from formula to determine passenger-car equivalent flow rate

\[ v_p = \frac{V}{PHF \times f_G \times f_{HV}} \]

- Peak-hour factor (PHF) and grade adjustment \((f_G)\) factor assumed to be one

- Heavy vehicle factor \((f_{HV})\) becomes \((E_T)^{-1}\), assuming proportion of trucks & buses equals 1
Truck Capacity

• After considering these assumptions, the formula to calculate truck capacity is

\[ v_t = \frac{\lambda v_p}{E_T} \times 24 \]

• The passenger-car flow rates \( v_p \) and equivalent factors \( E_T \) for specified terrains are taken from the Highway Capacity Manual

• \( \lambda \) is the number of lanes and the value 24 translates the hourly truck capacity to a daily truck capacity
Relative Truck Exposure Index (RTEI)

• The values calculated using the formula in slide 5 are transformed to a scale of 0-100 using the formula

\[
100 - \frac{RTEI}{\text{max}(RTEI)} \times 100
\]

• Lower values represent higher vulnerability
Relative Truck Exposure Index (RTEI)
Pavement Condition Rating Index (PCRI)

- Two pavement distresses considered to be correlated with the vulnerability of a road to commercial motor vehicles
  - Alligator Cracking
  - Rutting
Alligator Cracking

• Alligator cracking is a load associated structural failure

Source: NCDOT
Alligator Cracking

• Method used to calculate Alligator Cracking based on formula obtained from PMU @ NCDOT

• Derived from fields contained in PCS layer
  ✜ ALGTR_HGH_ – Severe Alligator Cracking
  ✜ ALGTR_MDRT – Moderate Alligator Cracking
  ✜ ALGTR_LOW_ – Low Alligator Cracking

• Calculated on a scale of 0-100

• Lower values represent more severe Alligator Cracking
Rutting

• Rutting is defined as having a surface depression in the wheel paths or at the edge of pavement

Source: NCDOT
Rutting

- Method to calculate Rutting score obtained from NCDOT
- Derived from field contained in PCS layer

<table>
<thead>
<tr>
<th>Rutting Code</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (N)</td>
<td>100</td>
</tr>
<tr>
<td>Low (L)</td>
<td>90</td>
</tr>
<tr>
<td>Moderate (M)</td>
<td>40</td>
</tr>
<tr>
<td>Severe (S)</td>
<td>0</td>
</tr>
</tbody>
</table>
Pavement Condition Rating Index (PCRI)

• If overall pavement rating <= 50, multiple distresses involved

• Factor in NCDOT’s overall pavement rating into PCRI

• PCRI calculated on scale of 0-100

\[
PCRI = \begin{cases} 
\frac{A + R}{2} \times \frac{RTG}{100} & \text{if } RTG \leq 50 \\
\frac{A + R}{2} & \text{if } RTG > 50 
\end{cases}
\]
Pavement Condition Rating Index (PCRI)
Bridge Severity Index (BSI)

- Bridge layer obtained from NCDOT

- Every bridge given a Bridge Rating ($BR$)

- Function of two components obtained from NCDOT bridge layer
  - Bridge distress ($D_j$)
  - Posted weight ($W_j$)

$$BR_j = 0.2D_j + 0.8W_j$$
Bridge Distress ($D_j$)

- Two bridge distresses defined in layer
  - Structurally Deficient (SD)
    "... if it is in relatively poor condition, or has insufficient load-carrying capacity. The insufficient load capacity could be due to the original design or to deterioration." (NCDOT)

  A bridge that is SD is given a Bridge Distress value of 100

  - Functionally Obsolete (FO)
    "... if it is narrow, has inadequate under-clearances, has insufficient load-carrying capacity, is poorly aligned with the roadway, and can no longer adequately service today’s traffic.” (NCDOT)

  A bridge that is only FO is given a Bridge Distress value of 33

  - A bridge that is neither SD nor FO is given a Bridge Distress value of 0
**Posted Weight ($W_j$)**

- Determined by how far below 45 tons a bridge’s posted weight is

- 45 tons is the maximum weight allowable in the state without a permit

- Transformed to a scale of 0-100

$$100 \frac{W_j}{\max(W_j)}$$

- The lower a bridge’s posted weight, the more vulnerable it is to oversize/overweight trucks
Bridge Severity Index (BSI)

- Combine individual Bridge Ratings together to obtain a cumulative BSI

- Ensures all bridges included

- Want to ensure that segments with most vulnerable bridges designated as such

\[
BSI = \max_j (BR) + \sum_{j \neq \max} \frac{BR_j}{10}
\]
Bridge Severity Index (BSI)

- Cumulative BSI scaled to 0-100 using linear transformation

\[ 100 - \frac{BSI}{\max(BSI)} \times 100 \]

- Lower values represent higher vulnerability
Bridge Severity Index (BSI)

- 0 - 53
- 54 - 65
- 66 - 77
- 78 - 89
- 90 - 100

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ALAMANCE

ORANGE
Road Vulnerability Index

- **RVI**
  - RTEI
    - Truck Count
    - Truck Capacity
  - PCRI
    - Alligator Cracking
    - Rutting
  - BSI
    - Bridge Rating
    - Bridge Distress
    - Posted Weight

- GIS
RVI Integration

• Components described are combined to obtain RVI using following formula

\[ RVI = \frac{\alpha RTEI + \beta PCRI + \gamma BSI}{\alpha + \beta + \gamma} \]

• Initial RVI, coefficients assumed to be 1

• Lower values represent higher vulnerability
Initial RVI
Baseline RVI

- Before determining weights of individual components, bias needs to be removed.

- Goal was to ensure percent variation in RVI equally explained by each of the individual component indices.

\[ \varepsilon = (\rho_{BSI} - \rho_{RTEI})^2 + (\rho_{RTEI} - \rho_{PCRI})^2 \]
Baseline RVI

• Minimizing equation on previous slide results in baseline model

\[
RVI = \frac{2.05 \times RTEI + 1.39 \times PCRI + 1.96 \times BSI}{5.40}
\]

⇒ Relative Truck Exposure Index (RTEI)

⇒ Pavement Condition Ratings Index (PCRI)

⇒ Bridge Severity Index (BSI)
Baseline RVI

- 31 - 72
- 73 - 81
- 82 - 90
- 91 - 99
- > 99
Sensitivity Analysis

- Sensitivity analysis performed to determine how stable the model is
- Average of each component perturbed by 5%

<table>
<thead>
<tr>
<th></th>
<th>RTEI</th>
<th>PCRI</th>
<th>BSI</th>
<th>RVI</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>91.52</td>
<td>89.92</td>
<td>89.06</td>
<td>90.22</td>
<td></td>
</tr>
<tr>
<td>$\mu_{[\text{RTEI}]} + 5%$</td>
<td>96.10</td>
<td>89.92</td>
<td>89.06</td>
<td>91.95</td>
<td>1.93%</td>
</tr>
<tr>
<td>$\mu_{[\text{PRCI}]} + 5%$</td>
<td>91.52</td>
<td>94.42</td>
<td>89.06</td>
<td>91.37</td>
<td>1.28%</td>
</tr>
<tr>
<td>$\mu_{[\text{BSI}]} + 5%$</td>
<td>91.52</td>
<td>89.92</td>
<td>93.51</td>
<td>91.83</td>
<td>1.79%</td>
</tr>
</tbody>
</table>
Summary

• Developed methodology that shows how to combine disparate datasets to produce a single layer for operational planning

• Framework for building when data is more complete

• The model is portable

• Additional components?
  - Geometric design
  - Grade
  - Lane width
Questions?

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