Sampling Based Approach for Incorporating Road Capacity Uncertainties into Transportation Planning

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Outline

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  – Motivation
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  – Formulation
  – Approach

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  – Comparison, and analysis

• TWO APPLICATION
  – Evacuation time estimate
  – Critical link detection and ranking
INTRODUCTION
Background

- Transportation Planning
  - Evaluation, assessment, design and siting of transportation facilities
  - Key part: travel demand forecasting (4-step model)

- Road Capacity Uncertainty
  - capacity reduction due to various events, e.g. weather, accident…
  - capacity distributions for certain time period, e.g. one year
Motivation

• Challenges: Incorporate capacity uncertainty into planning process

  ✓ Proactive vs. Reaction
  ✓ Current: “expected” result under assumed normal condition
  ✓ Key: data collection and efficient computation

Current Work

- **Uncertainty impact on Traffic Assignment**
  - Yong and Kara (2001) investigated the uncertainty impact on the four step model, the result indicated that uncertainty was likely to compound itself over a series of models.
  - Waller et al. (2001) and Ukkusuri and Waller (2006) described and discussed demand uncertainty on traffic assignment problem.
  - Yazici and Ozbay (2010) – Capacity Uncertainty on Dynamic Traffic Assignment

- **Several applications**
  - Evacuation Planning.
  - Critical link detection.
  - Safety conscious planning
MATHEMATICAL FORMULATION
Mathematical Formulation

• The problem can be formulated as a stochastic optimization problem of the form:

\[
SP \quad z^* = \min_{x \in X} \frac{1}{n} \sum_{i=1}^{n} f(x, \tilde{\xi}^i) \quad \text{with} \quad x^* \in \arg \min_{x \in X} \frac{1}{n} \sum_{i=1}^{n} f(x, \tilde{\xi}^i)
\]

where \( f \) is the function that represents the outcome of the traditional traffic assignment (User Equilibrium or System Equilibrium), \( x \) is the vector of link flow, and \( \tilde{\xi} \) is the vector of link capacity, which is random variable.

• The above \( SP \) can be approximately solved by sampling technique.

\[
SP \quad z^* = \min_{x \in X} \frac{1}{n} \sum_{i=1}^{n} f(x, \tilde{\xi}^i) \quad \text{with} \quad x^* \in \arg \min_{x \in X} \frac{1}{n} \sum_{i=1}^{n} f(x, \tilde{\xi}^i)
\]

where \( \tilde{\xi}^i, i = 1, \ldots, n \), are independent and identically distributed (i.i.d) from the distribution of \( \tilde{\xi} \)
Mathematical Formulation of the Static System Optimal Assignment Problem

Minimize \( E(\sum_a x_a t_a(x_a, c_a)) \)

subject to \( \sum_k f^r_s = q_{rs} \)

\( x_a = \sum_r \sum_s \sum_k \delta^{rs}_{a,k} f^r_s \)

\( c_a = c^\sim_a, \forall a \in A \)

\( f^r_s \geq 0 : \text{for all } k, r, s \)

\( x_a \geq 0, \forall a \in A \)

\( \delta^{rs}_{a,k} = 1 \text{ if } a \in k, \text{else } \delta^{rs}_{a,k} = 0 \)

Where

- \( c_a \) is the link capacity, which is a random variable follows certain distribution, define as \( c^\sim_a \).

- \( f^r_s \) is flow on path \( k \) connecting O-D pair \( r-s \), \( q_{rs} \) is total number of trips between \( r \) and \( s \), \( x_a \) is equilibrium flows on the link \( a \), and \( t_a(x_a, c_a) \) is link performance function (travel time) on link \( a \). \( c_a \) is the link capacity.
Proposed Methodological Approach

FIGURE 1 Representation of SAA Solution Steps
SAMPLING APPROACH
Sampling Methods

• Five sampling techniques were compared
  ✓ Goals
    ▪ The accuracy and convergence rate
  ✓ Sampling techniques:
    ▪ Monte Carlo (MC)
    ▪ Antithetic variants (ANT),
    ▪ Latin hypercube sampling (LHS)
    ▪ Quasi-Monte Carlo (QMC) with different sequences:
      ▪ Sobol’ (SOB)
      ▪ Faure (FAU)
      ▪ Hammersley (HAM)
      ▪ Niederreiter (NIE)
  ✓ Network:
    ▪ Nguyen–Dupuis Network
    ▪ Link capacity follows Weibull Distribution.
  ✓ Accuracy measure

\[ \text{Accuracy (percent deviation)} = \left| \frac{z_n - z^*}{z^*} \right| \]

▪ Benchmark \( z^* \): 10,000 Monte Carlo runs.
Sampling Methods

- **Monte Carlo**
  - Most common and widely used method for sampling

- **Antithetic variants**
  - For each time, generate two negatively correlated pairs of samples of the random parameter to arrive at the necessary estimate

- **Latin hypercube sampling**
  - Divide parameter range in m intervals, randomly sample m points in a way that each interval has 1 point, change at each Latin Hypercube point each parameter one by one

- **Quasi-Monte Carlo**
  - A deterministic counterpart to the MC. Based on low discrepancy sequences from d-dimensional unit hypercube instead of random point set in MC

Reference:
Sampling Results for the Nguyen-Dupuis Network

• Conclusion
  ✓ The error rates for all sampling methods are below 0.04% for more than 3000 samples.
  ✓ LHS is found to be an efficient sampling technique based on accuracy and convergence rate.
APPLICATION 1: Evacuation Time Estimate
Evacuation Scenario

• No-Notice Evacuation
  ▪ Scenario: Improvised Explosive Device in Newark International Airport
  ▪ Evacuation time estimate: Time traced from evacuation zone to safe zone.
Network
Capacity Reduction due to Accident

- **HCM 2000**
  - Summarized studies by Reiss and Dunn (1991) and Gordon et al. (1996), as below:

<table>
<thead>
<tr>
<th>Number of Freeway Lanes by Direction</th>
<th>Shoulder Disablement</th>
<th>Shoulder Accident</th>
<th>One Lane Blocked</th>
<th>Two Lanes Blocked</th>
<th>Three Lanes Blocked</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.81</td>
<td>0.35</td>
<td>0.00</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.83</td>
<td>0.49</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>0.99</td>
<td>0.85</td>
<td>0.58</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>5</td>
<td>0.99</td>
<td>0.87</td>
<td>0.65</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>6</td>
<td>0.99</td>
<td>0.89</td>
<td>0.71</td>
<td>0.50</td>
<td>0.26</td>
</tr>
<tr>
<td>7</td>
<td>0.99</td>
<td>0.91</td>
<td>0.75</td>
<td>0.57</td>
<td>0.36</td>
</tr>
<tr>
<td>8</td>
<td>0.99</td>
<td>0.93</td>
<td>0.78</td>
<td>0.63</td>
<td>0.41</td>
</tr>
</tbody>
</table>

- **Brian et al (2003)**
  - Updated HCM 2000 with more detailed accident database with three-lane freeway segment. However, the conclusion still needs to be confirmed and updated on other freeway segments.
Capacity Reduction due to Weather Conditions

- Previous research (Okamoto et al. (2004), Smith et al. (2004), Manish et al. (2005)) emphasized the influence of extreme weather intensity values in capacity reduction. Although the value of capacity reduction might be slight different, the tendency is converge.

<table>
<thead>
<tr>
<th>Studies</th>
<th>Weather</th>
<th>Intensity</th>
<th>Capacity Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCM (2000)</td>
<td>Rain &amp; Snow</td>
<td>Light &amp; heavy</td>
<td>0% and 15% for light and heavy rains, 5%-10% and 25%-30% for light and heavy snow conditions. 0%, 5%, 11%, 14%, 25% and 33% for the rain intensity 0.0, 0.01-0.06, 0.07-0.12, 0.13-0.24, 0.25-0.48, and 0.49-0.96 cm/hour precipitation.</td>
</tr>
<tr>
<td>Okamoto et al. (2004)</td>
<td>Rain</td>
<td>Intensity groups</td>
<td>Trace (&lt;0.01) 4%-10% and 25%-30% for light and heavy rain.</td>
</tr>
<tr>
<td>Smith et al. (2004)</td>
<td>Rain</td>
<td>Light (0.01-0.25)</td>
<td>1%-3%, 5%-10%, 10%-17% for trace, light and heavy rain; 3%-5%, 6%-11%, 7%-13% for trace, light and moderate snow, 19%-27% for heavy snow (&gt;0.5 inch/hr).</td>
</tr>
<tr>
<td>Manish et al. (2005)</td>
<td>Rain &amp; Snow</td>
<td>Light (0.01-0.25) Heavy (&gt;0.25)</td>
<td>2.9%, 7.9% and 5.2% on weekdays, Saturdays and Sundays</td>
</tr>
<tr>
<td>Chung et al. (2005)</td>
<td>Rain</td>
<td>13 mm/day</td>
<td>4-7% in light rain, maximum 14% during heavy rain.</td>
</tr>
</tbody>
</table>
Capacity Reduction

• Accident
  ✔ HCM 2000 recommendation was used in this study
  ✔ Since data is unavailable, accident duration was assumed to follow uniform distribution U (30, 60) and all the accidents block one lane only.

• Extreme Weather
  ✔ Based on the summary, capacity reduction can be seen as below

<table>
<thead>
<tr>
<th>Weather Condition</th>
<th>Rain</th>
<th>Snow</th>
<th>Clear</th>
<th>others</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trace (&lt;0.01)</td>
<td>Light [0.01-0.25]</td>
<td>Heavy (&gt;0.25)</td>
<td>Trace (&lt;0.01)</td>
</tr>
<tr>
<td>Capacity Reduction</td>
<td>1-5%</td>
<td>5%-10%</td>
<td>10%-15%</td>
<td>5%-10%</td>
</tr>
</tbody>
</table>
Link Capacity Distributions

• Capacity Distribution Fit
  ✓ Kolmogorov-Smirnov
  ✓ Anderson-Darling
  ✓ Chi-Squared

• High Accident Rate Link (up)
  ✓ Gen Extreme Value
  ✓ Gumbel Min
  ✓ Log-logistic

• Low Accident Rate Link (down)
  ✓ Gen Extreme Value
  ✓ Weibull
  ✓ Gumbel Min
Evacuation Time Estimates
APPLICATION 2: Critical Link Detection
Current Work

• Theoretical work in Operation Research
  – Performance measure:
    • the increase of the shortest path length (Malik et al., 1989, Ball et al., 1989 and Barton, 2005)
  – The most vital arcs problem as the determination of the subset of arcs whose removal from the network results in the greatest increase in the shortest path length.

• Critical link detection for transportation
  – Bi-level model formulation
    • Lower Level: traffic assignment based on user equilibrium
    • Upper Level: maximize disruption to the network.
  – Performance measures
    • Accessibility
    • Economy
Motivation

• Capture critical link with day-to-day conditions
  ✔ Current:
    ▪ Result assumed normal condition, or worst condition by complete fail.
    ▪ Applicable for emergency situation
  ✔ Day-to-day condition:
    ▪ Weather
    ▪ Incident/accident
    ▪ …
  ✔ Key Points
    ▪ Multi-states for degradable links
    ▪ Combination effects

Proposed Methodological Approach

- For each link:
  - Reduction Factor 1
  - Reduction Factor 2
  - ...
  - Reduction Factor N

1. Network Formulation
2. Link Capacity Distribution
3. Sampling Technique
4. Link Capacity Realization
5. Static Assignment
6. Sample Size Satisfied? (Yes/No)
7. Sensitivity Analysis
Sensitivity Analysis

• Rank Transformation\textsuperscript{[1]}
  – Nonlinear travel time function
  – Convert nonlinear but monotonic relationship into linear relationship
    • data $\leftrightarrow$ ranks
    • smallest value $\leftrightarrow$ rank 1
    • the 2\textsuperscript{nd} smallest value $\leftrightarrow$ rank 2
    • ...

• Sensitivity Analysis Measures\textsuperscript{[2]}
  – rank correlation coefficients (RCCs)
  – standardized rank regression coefficients (SRRCs)
  – partial rank correlation coefficients (PRCCs)

Reference:
Results

- Criticality Measure Vs. V/C Ratio
  - V/C ratio cannot capture criticality
  - Route Choice: Highway Vs. Local?

<table>
<thead>
<tr>
<th>Links</th>
<th>Name</th>
<th>RCC p-Value</th>
<th>RCC Rank</th>
<th>SRRC p-Value</th>
<th>SRRC Rank</th>
<th>PRCC p-Value</th>
<th>PRCC Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>US-1&amp;9</td>
<td>0.0000</td>
<td>1</td>
<td>0.0000</td>
<td>1</td>
<td>0.0000</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Rahway Ave(I-27)</td>
<td>0.0041</td>
<td>2</td>
<td>0.0000</td>
<td>2</td>
<td>0.0129</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>I-78</td>
<td>0.0058</td>
<td>3</td>
<td>0.0000</td>
<td>3</td>
<td>0.2473</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>I-95</td>
<td>0.1206</td>
<td>4</td>
<td>1.9376</td>
<td>5</td>
<td>1.5652</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Westfield Ave(I-28)</td>
<td>0.3284</td>
<td>5</td>
<td>1.9854</td>
<td>6</td>
<td>1.4726</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>I-95</td>
<td>0.3681</td>
<td>6</td>
<td>1.4456</td>
<td>4</td>
<td>1.1405</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>US-1&amp;9</td>
<td>0.7939</td>
<td>7</td>
<td>2.0000</td>
<td>8</td>
<td>1.9453</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>Morris Ave(I-82)</td>
<td>0.8391</td>
<td>8</td>
<td>2.0000</td>
<td>7</td>
<td>1.9257</td>
<td>7</td>
</tr>
<tr>
<td>19</td>
<td>Elizabeth Ave</td>
<td>0.9052</td>
<td>9</td>
<td>2.0000</td>
<td>9</td>
<td>1.9952</td>
<td>9</td>
</tr>
<tr>
<td>9</td>
<td>I-27</td>
<td>1.7886</td>
<td>10</td>
<td>2.0000</td>
<td>11</td>
<td>1.9998</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>I-22</td>
<td>1.8371</td>
<td>11</td>
<td>2.0000</td>
<td>10</td>
<td>1.9989</td>
<td>10</td>
</tr>
</tbody>
</table>
Conclusion and Future Research

• Conclusion
  ▪ The sampling-based analysis approach for capacity uncertainty analysis in degradable transportation network is proposed.
  ▪ Different sampling techniques are compared and Latin Hypercube Sampling is found to be an accurate and efficient methodology.
  ▪ Two applications are discussed

• Future research
  ▪ More applications to transportation problems e.g. network design.
  ▪ Extend the proposed approach to dynamic traffic assignment
Thanks for your Attention

or 🍅 🍆 ?