Presentation for ITM 2010

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Sampling Based Approach for Incorporating Road Capacity Uncertainties into Transportation Planning

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Outline

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  - Critical link detection and ranking

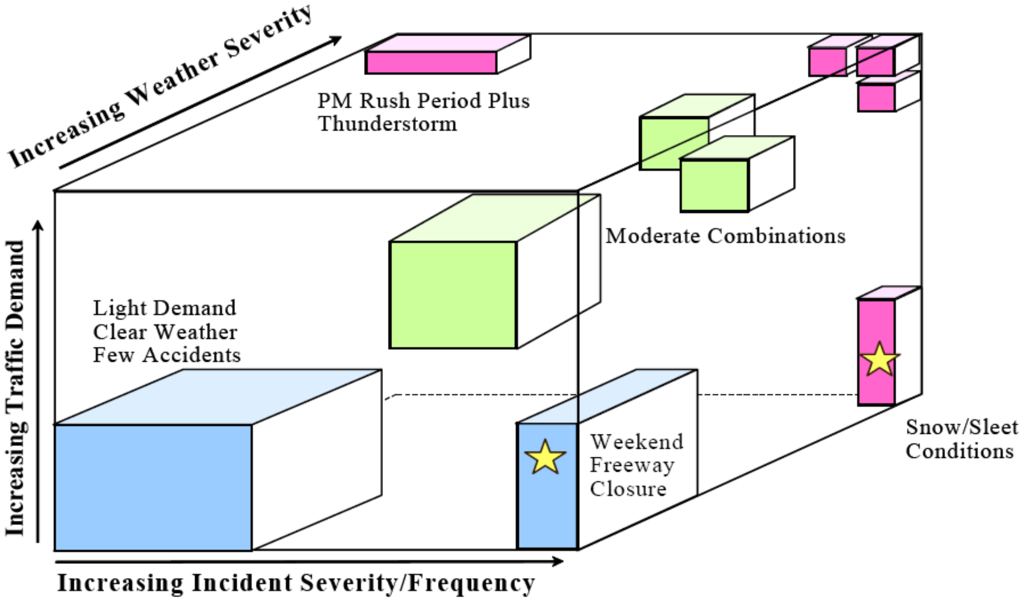
INTRODUCTION

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



Source: Wunderlich, K., et al., *Seattle 2020 Case Study*, PRUEVIIN Methodology, Mitretek Systems. This document is available at the Federal Highway Administration Electronic Data Library (http://www.itsdocs.fhwa.dot.gov/).

Current Work

- **Uncertainty impact on Traffic Assignment**
  - ✓ First proposed by Backmann, K., C. McGuire, and C. Winston. Studies in the Economics of Transportation. Yale University Press, New Haven, Conn., 1956.
  - ✓ 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.
    - Ozbay and Yazici (2007), Robinson et al. (2009) .
  - ✓ Critical link detection.
    - Bell (1999), Jenelius et al. (2006) , Murray and Mahmassani (2007), Nagurney and Qiang (2007).
  - ✓ Safety conscious planning
    - Chatterjee et al. (2000), Lord and Persaud (2004), Kononov and Allery (2004), Gaines (2007).

MATHEMATICAL FORMULATION

Mathematical Formulation

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

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

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.

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

where $\tilde{\xi}^i, i = 1,\ldots, n$, are independent and identically distributed (i.i.d) from the distribution of $\tilde{\xi}^i$

Mathematical Formulation of the Static System Optimal Assignment Problem

$$\text{Minimize } E\left(\sum_a x_a\, t_a(x_a, c_a)\right)$$

$$\text{subject to } \sum_k f_k^{rs} = q_{rs}$$

$$x_a = \sum_r \sum_s \sum_k \delta_{a,k}^{rs} f_k^{rs}$$

$$c_a = c_a^{\sim}, \forall a \in A$$

$$f_k^{rs} \geq 0 : \text{for all } k, r, s$$

$$x_a \geq 0, \forall a \in A$$

$$\delta_{a,k}^{rs} = 1 \text{ if } a \in k, \text{else } \delta_{a,k}^{rs} = 0$$

Where

c_a is the link capacity, which is a random variable follows certain distribution, define as $c_a^{\sim}$.

f_k^{rs} 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

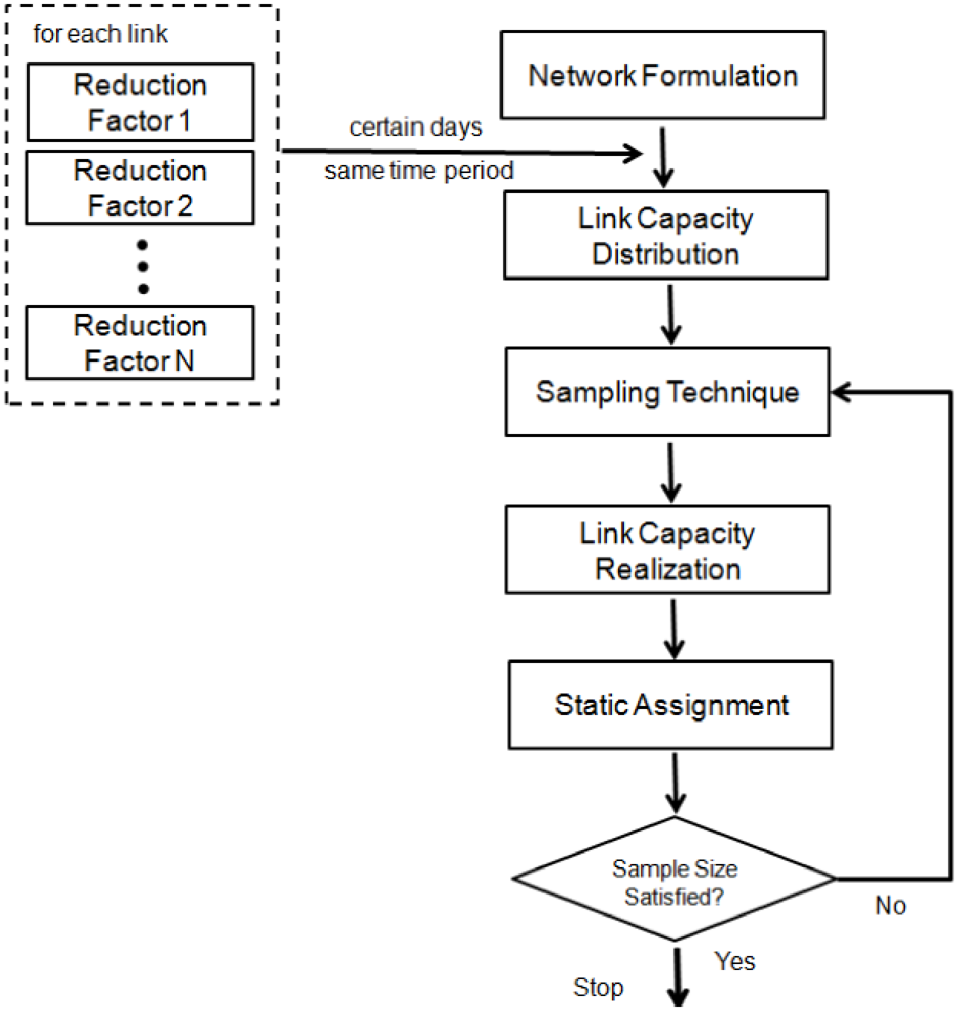


FIGURE 1 Representation of SAA Solution Steps

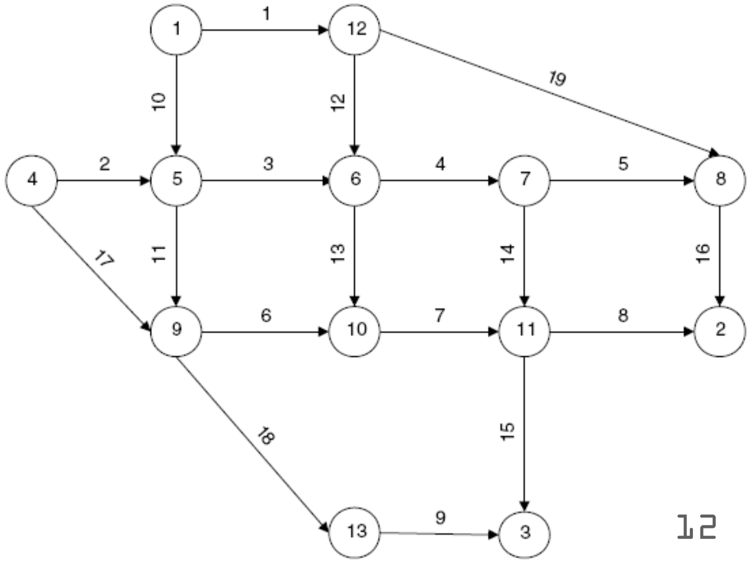
SAMPLING APPROACH

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)
      - Nidederreiter (NIE)
  - ✓ Network:
    - Nguyen–Dupuis Network
    - Link capacity follows Weibull Distribution.
  - ✓ Accuracy measure

$$Accuracy(percent\ deviation) = \left|\frac{\overline{z_n} - z^*}{z^*}\right|$$

- 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

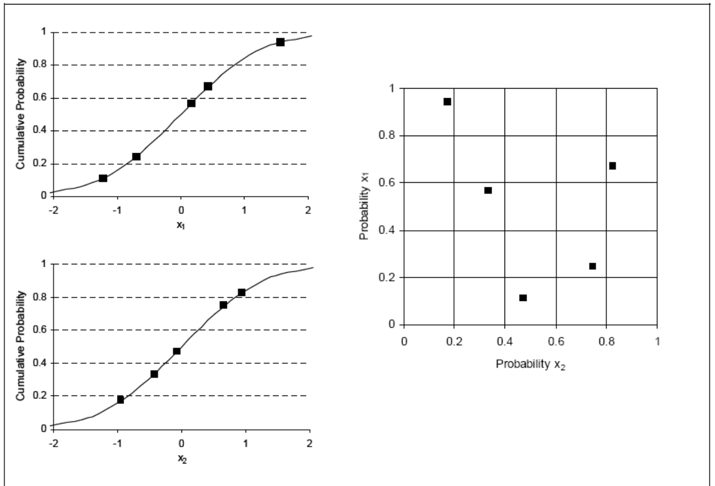
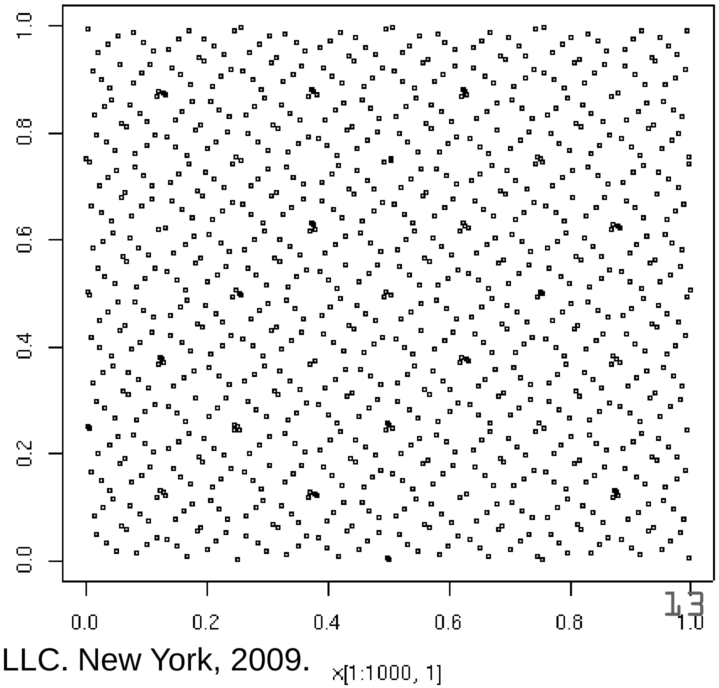


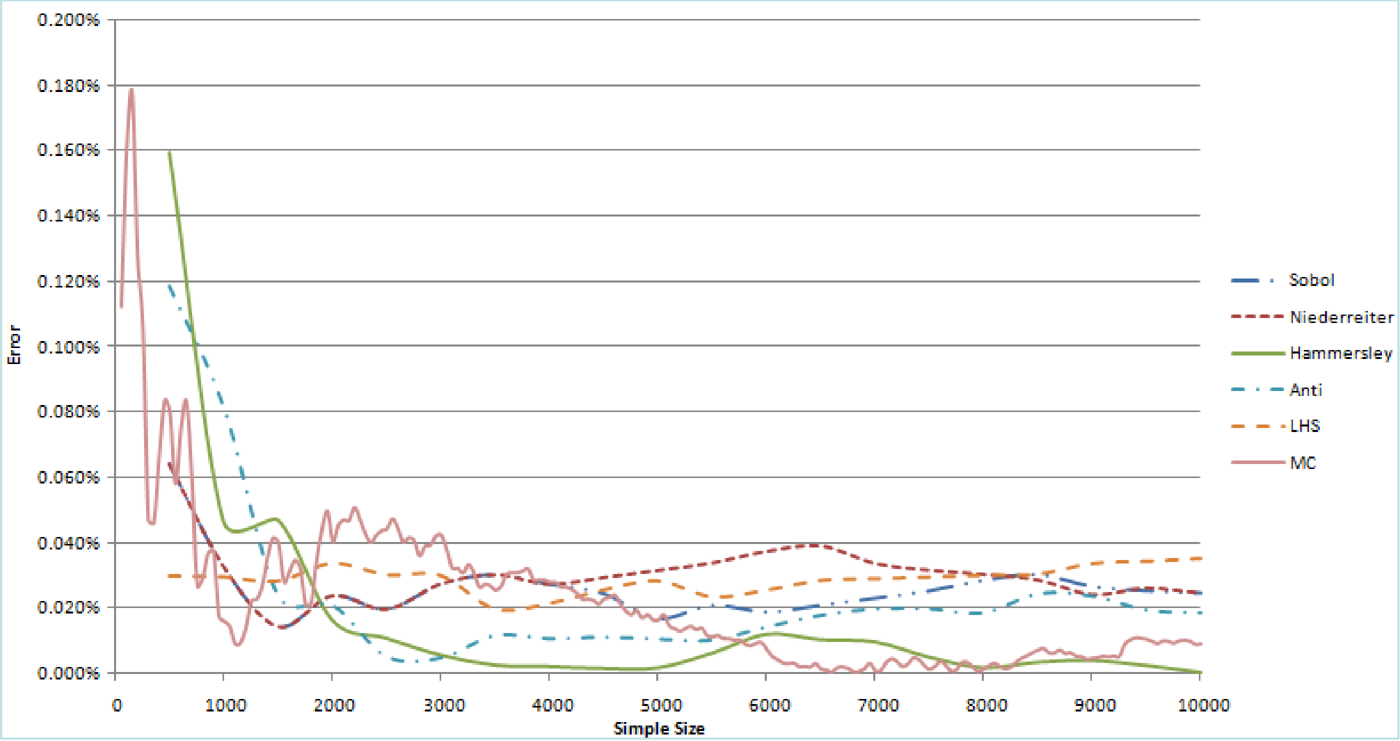
Fig. 1. Example of LHS: Random stratified sampling of variables x_1 and x_2 at 5 intervals (Left) and random pairing of sampled x_1 and x_2 forming a Latin hypercube (Right).



Reference:
[1] Lemieux, C. *Monte Carlo and Quasi-Monte Carlo Sampling*. Springer, LLC. New York, 2009.

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

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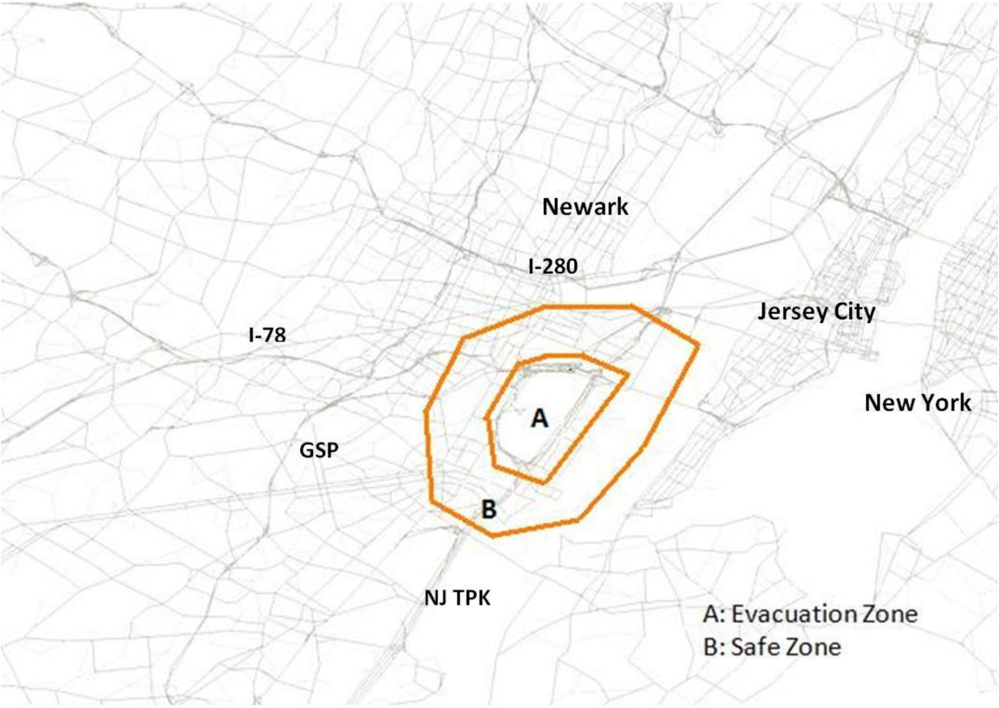
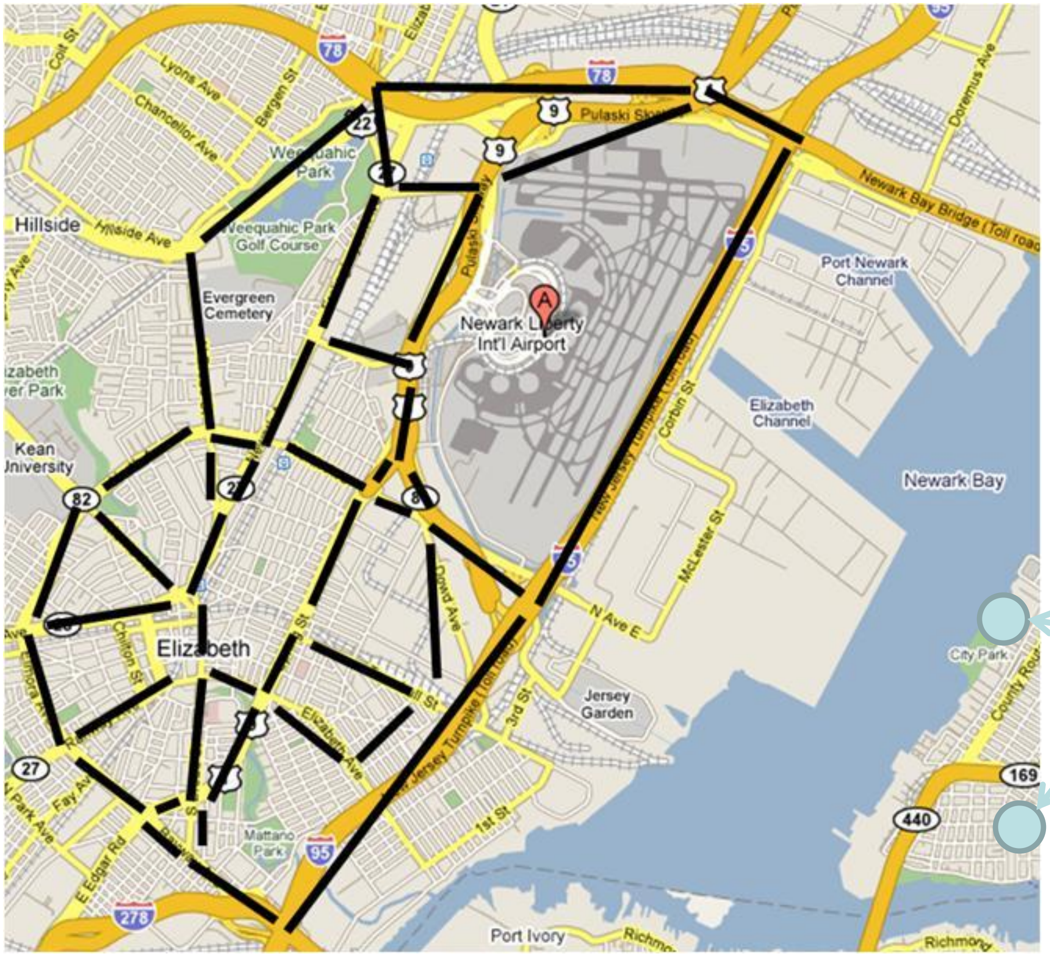
Evacuation Scenario

- No-Notice Evacuation
  - Scenario: Improvised Explosive Device in Newark International Airport
  - Evacuation time estimate: Time traced from evacuation zone to safe zone.



Network


Hillside
Hillside Ave
Weequahic Park
Weequahic Park Golf Course
Evergreen Cemetery
Kean University
Elizabeth
Newark Liberty Int'l Airport
Pulaski Skwy
Port Newark Channel
Elizabeth Channel
Newark Bay
Newark Bay Bridge (Toll road)
Jersey Garden
Port Ivory
City Park
Doremus Ave
McLester St
Corbin St
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1st St
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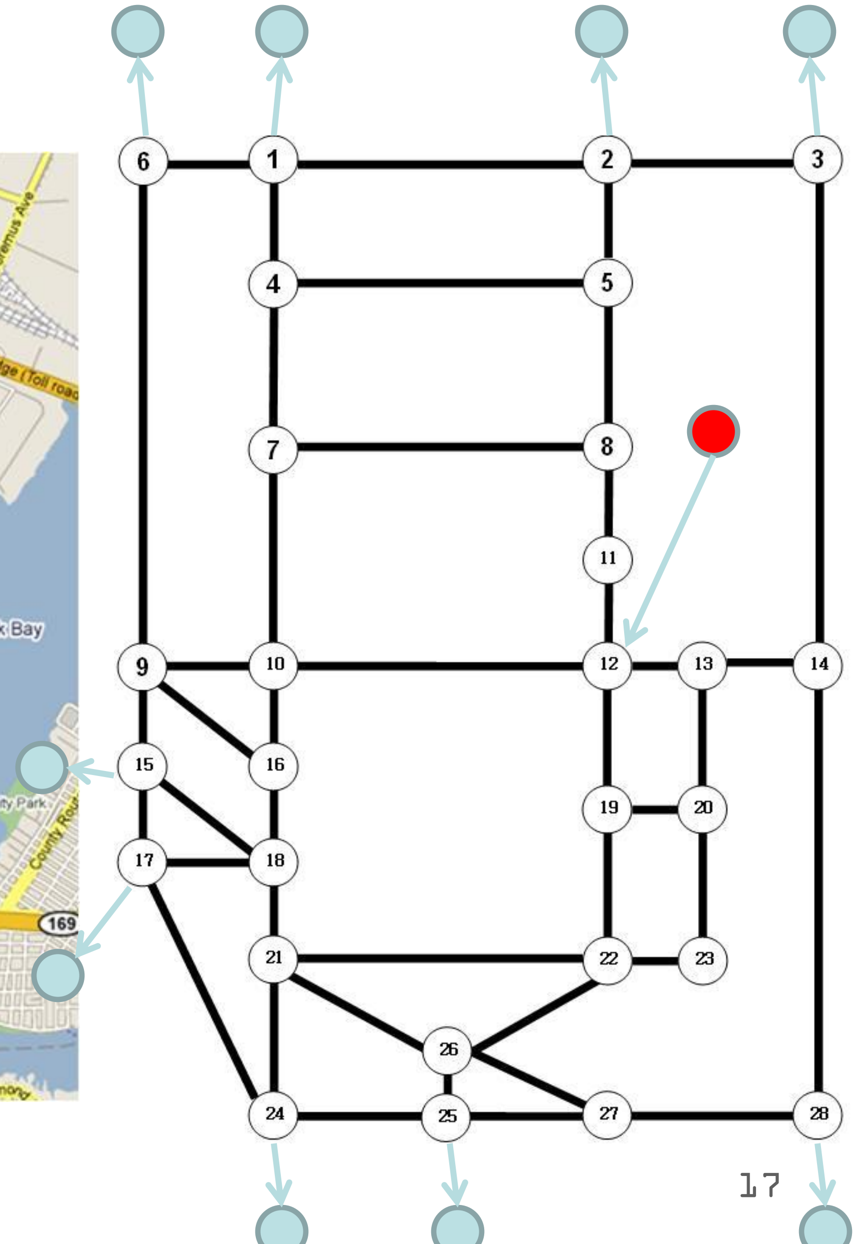
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Capacity Reduction due to Accident

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

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

- 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.

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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.

Summary of Capacity Reduction due to Extreme Weather Condition

Studies	Weather	Intensity	Capacity Reduction
HCM (2000)	Rain & Snow	Light & heavy	0% and 15% for light and heavy rains, 5%-10% and 25%-30% for light and heavy snow conditions.
Okamoto et al. (2004)	Rain	Intensity groups	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.
Smith et al. (2004)	Rain	Trace (<0.01) Light (0.01-0.25) Heavy (>0.25)	4%-10% and 25%-30% for light and heavy rain.
Manish et al. (2005)	Rain & Snow	Trace (<0.01) Light (0.01-0.25) Heavy (>0.25)	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 (>0.5 inch/hr).
Chung et al. (2005)	Rain	13 mm/day	2.9%, 7.9% and 5.2% on weekdays, Saturdays and Sundays
Chung et al. (2006)	Rain	Light & heavy	4-7% in light rain, maximum 14% during heavy rain.

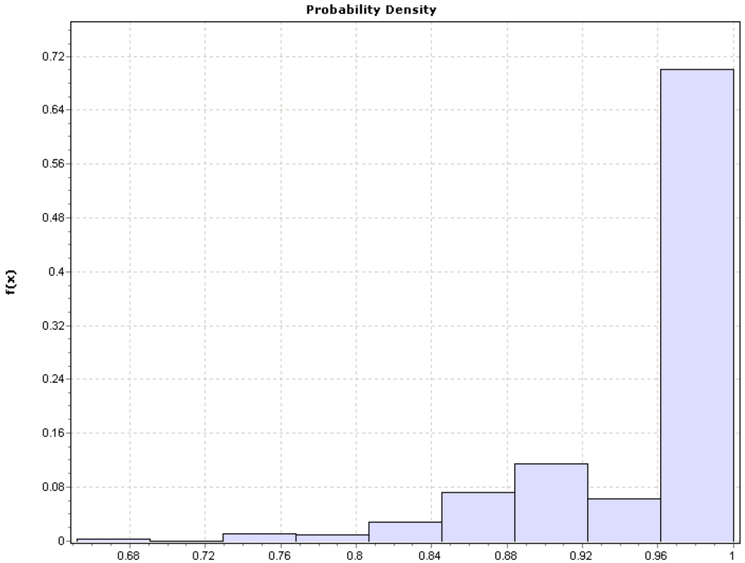
Capacity Reduction

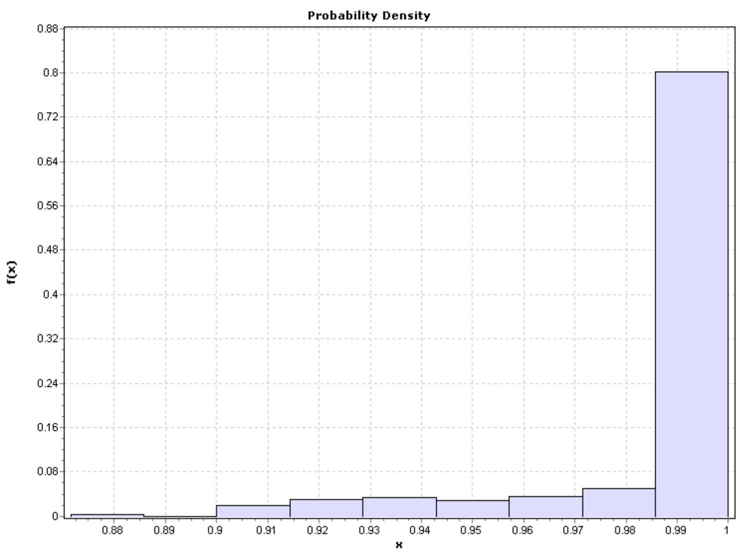
- Accident
  - ✓HCM 2000 recommendation was used in this study
  - ✓Since data is unavailable, accident duration was assumed to follow uniform distribution U (30, 60) and all the accidents block one lane only.
- Extreme Weather
  - ✓Based on the summary, capacity reduction can be seen as below

Weather Condition	Rain			Snow			Clear	others
	Trace (<0.01)	Light [0.01-0.25]	Heavy (>0.25)	Trace (<0.01)	Light [0.01,0.25]	Heavy (>0.25)		
Capacity Reduction	1-5%	5%-10%	10%-15%	5%-10%	10%-15%	15%-20%	0%	1-5%

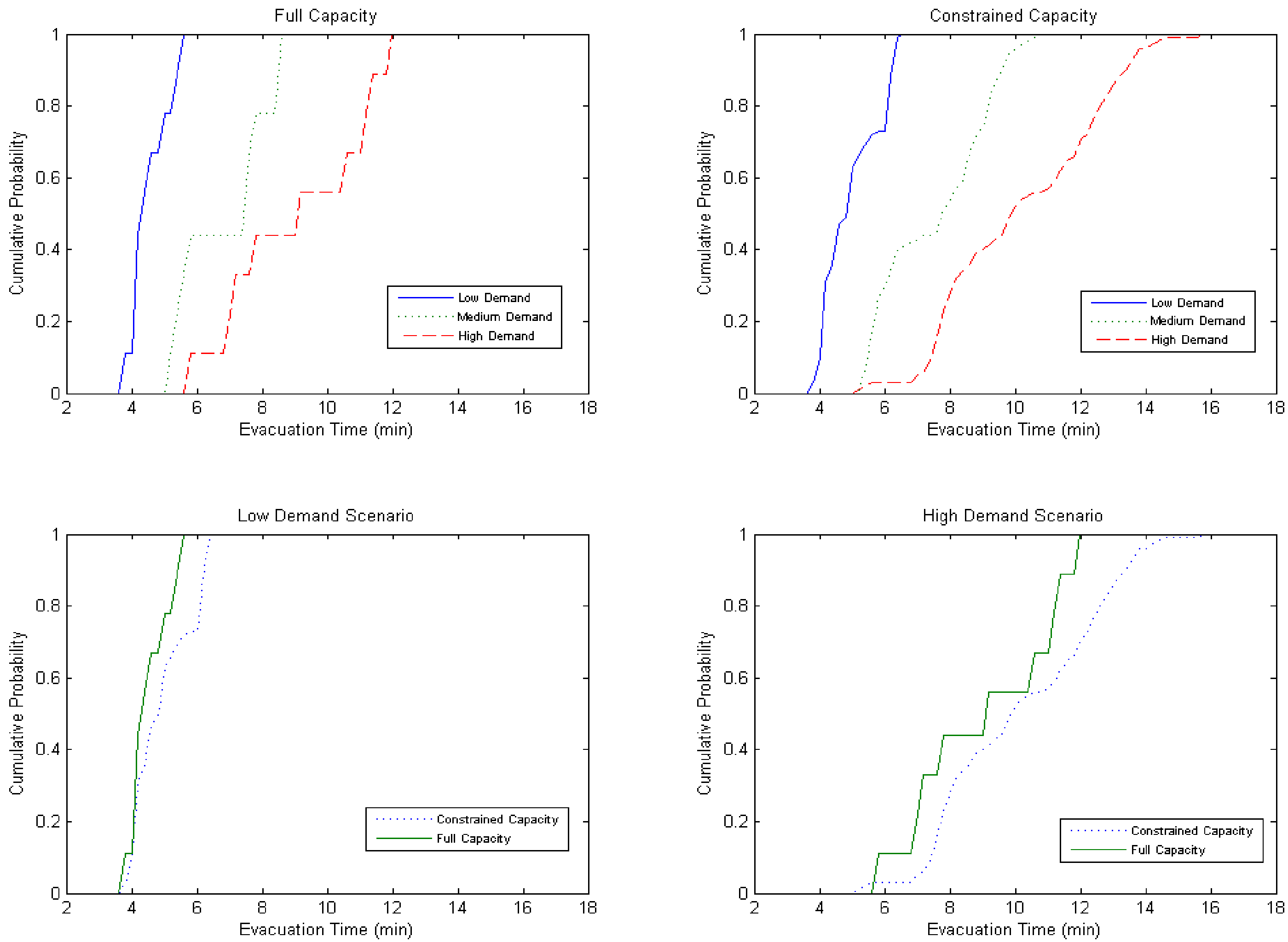
Link Capacity Distributions

- 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

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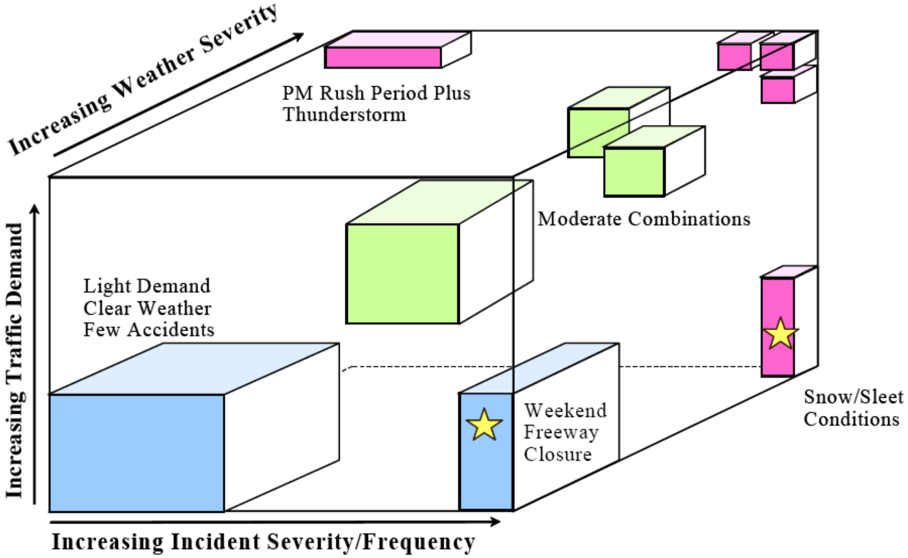
Motivation

- 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



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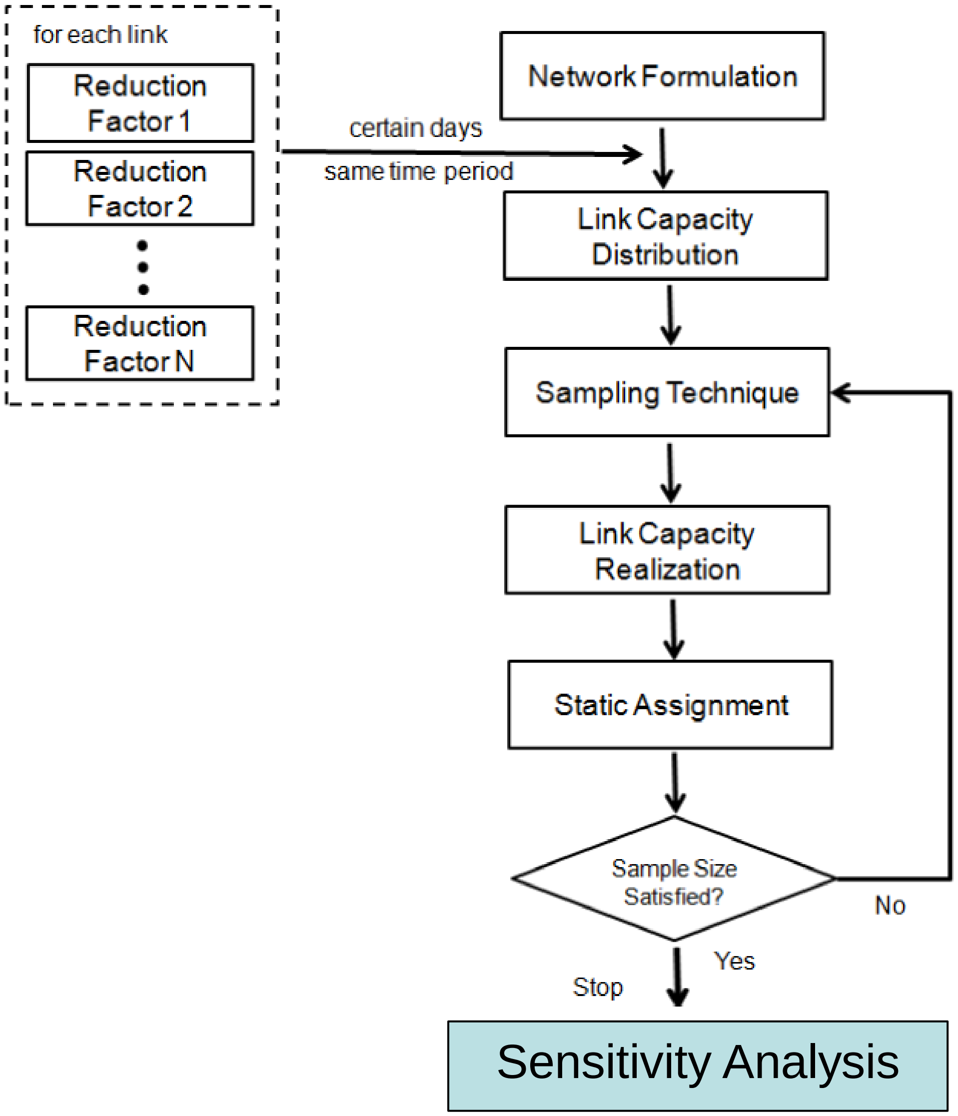
Proposed Methodological Approach



Sensitivity Analysis

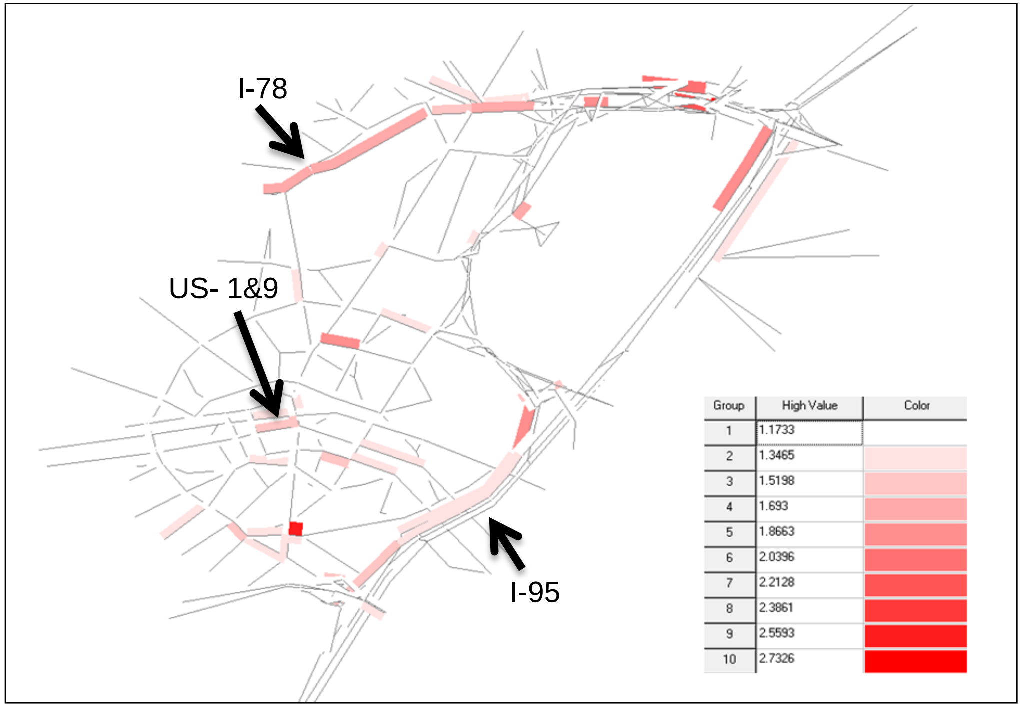
- Rank Transformation[1]
  - Nonlinear travel time function
  - Convert nonlinear but monotonic relationship into linear relationship
    - data ⟷ ranks
    - smallest value ⟷ rank 1
    - the 2nd smallest value ⟷ rank 2
    - …
- Sensitivity Analysis Measures[2]
  - rank correlation coefficients (RCCs)
  - standardized rank regression coefficients (SRRCs)
  - partial rank correlation coefficients (PRCCs)

Reference:
[1] Andrea Saltelli and Sobol'. *About the Use of Rank Transformation in Sensitivity Analysis of Model Output. Reliability Engineering and System Safety,* Vol.50, 1995, pp. 225-239.
[2] J.C. Helton, J.D. Johnson, C.J. Sallaberry and C.B. Storlie. *Survey of Sampling-based Methods for Uncertainty and Sensitivity Analysis.* Reliability Engineering and System Safety, vol.91, 2006, pp. 1175-1209.

Results

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

Links	Name	RCC		SRRC		PRCC	
		p-Value	Rank	*p*-Value	Rank	*p*-Value	Rank
5	US-1&9	0.0000	1	0.0000	1	0.0000	1
8	Rahway Ave(I-27)	0.0041	2	0.0000	2	0.0129	2
1	I-78	0.0058	3	0.0000	3	0.2473	3
6	I-95	0.1206	4	1.9376	5	1.5652	6
3	Westfield Ave(I-28)	0.3284	5	1.9854	6	1.4726	5
7	I-95	0.3681	6	1.4456	4	1.1405	4
4	US-1&9	0.7939	7	2.0000	8	1.9453	8
2	Morris Ave(I-82)	0.8391	8	2.0000	7	1.9257	7
19	Elizabeth Ave	0.9052	9	2.0000	9	1.9952	9
9	I-27	1.7886	10	2.0000	11	1.9998	11
10	I-22	1.8371	11	2.0000	10	1.9989	10



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

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 or  ?