Travel Time Reliability: A Network-level Perspective

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Outline

- Reliability: complex micro interactions, simple collective effects?
  - Validating robust relation between SD and Mean

- Connection to Network Fundamental Diagram
  - Analytical derivation
  - Verification through simulation

- Network signature relations

- Network dynamics: hysteresis, loading cycles, and gridlock formation and propagation

- Concluding comments
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Modeling Variability and Its Sources in Traffic Simulation

**SIMULATION MODEL**

Laws of physics/human behavior to capture interactions over time and space (network)

\[ X(t) + \varepsilon_x(t) \]

\[ Y[X(t)] + \varepsilon_y(t | X) \]

**SYSTEMATIC and RANDOM VARIATION**
Modeling Variability and Its Sources in Traffic Simulation

**SIMULATION MODEL**

**PROCESSES**

- Individual level mechanisms
- Collective effects

**DEMAND**

- Event/ discrete
- Process/ continuous

**SUPPLY**

- Event/ discrete
- Process/ continuous

EXOGENOUS vs. ENDOGENOUS?
- Flow breakdown?
- Accidents?

Resultant variation reflected in vehicle trajectories
Incorporating Sources of Variability in Traffic Models

• Identify phenomena and behaviors that account for the observed variability in network traffic performance, and determine the most effective approach for modeling these phenomena at both microscopic and mesoscopic levels.

• For reliability analysis purposes, our framework unifies all particle-based simulation approaches so long as they produce vehicle trajectories.

• General modeling approach:
  – incorporate as much as possible (given state of art in traffic theories and behavioral models), the causal or systematic determinants of variability.
  – remaining inherent variation to be added through suitably calibrated probabilistic mechanisms.

• To increase the model’s usefulness and responsiveness to various reliability-improving measures, our philosophy is to push as much as possible the portion of the total variation from the unexplained (noise) side of the equation to the systematic observable portion.
Define Scenario $S$

Events
Realizations or Probabilities
Distributions of Parameters

$X_S$  \rightarrow  \text{SIMULATION MODEL}

\begin{align*}
\text{PROCESSES} \\
\text{Individual level mechanisms} \\
\text{Collective effects}
\end{align*}

$Y \mid S$

Trajectories basis for extracting characterizations of variability for reliability analysis

$f_Y (Y \mid S)$

EXOGENOUS vs. ENDOGENOUS?
To conduct an evaluation study:

• Define scenarios, with associated probability $P(S)$
• Simulate to obtain $Y|S$ and $f_Y(Y|S)$

$$E[Y] = \sum [Y|S] \times p(S)$$

$$f_Y(Y) = \sum f_Y(Y|S) \times p(S)$$
# Sources of Travel Time Variation

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|                   | - Closure of alternative modes | | - Dynamic pricing                        |}

### Scenario manager

- Demand
  - Special events
  - Day-to-day variation
  - Visitors
  - Closure of alternative modes

- Supply
  - Incidents
  - Work zones
  - Adverse weather

### Improvements to existing simulation tools

- Demand
  - Heterogeneity in Route Choice and User Responses to Information and Control Measures
  - Heterogeneity in vehicle type

- Supply
  - Flow breakdown and incidents
  - Heterogeneity in car following behavior
  - Traffic control
  - Dynamic pricing

### Performance measures

- Output
  - Travel time distribution
  - Reliability performance indicators
  - User-centric reliability measures
Traffic Simulation Models: *Capture Sources of Unreliability*

**Scenario Manager**
- Construct scenarios with various combinations of external events, demand, supply and traffic control elements.
- Construct “What-if” scenarios using Monte Carlo sampling.

**Trajectory Processor**
- Extract reliability-related measures from the vehicle trajectory output of the simulation models.
Scenario-based Reliability Analysis

Capture travel time variability by simulating multiple likely scenarios that reflect various exogenous sources of uncertainties in the road network.

Scenario 1

Scenario 2

Scenario N

\[ \Pr(S_1) \]

\[ \Pr(S_2) \]

\[ \Pr(S_N) \]
Complex interactions, Collective Effects:

Simple, robust relation between std. deviation and mean of trip time per unit distance
Complex interactions, Collective Effects

Relation between standard deviation of trip time per mile and mean trip time per unit distance
Travel Time Reliability

- **Model:** standard deviation vs. mean

\[ \delta(t') = \theta_1 + \theta_2 \cdot E(t') \]

where
\[ t' \text{= travel time per unit distance} \]
\[ \delta(t') \text{= standard deviation of } t' \]
\[ E(t') \text{= mean value of } t' \]
\[ \theta_1, \theta_2 \text{= coefficients} \]

- **Origins**
  - Suggested by Prigogine and Herman’s Kinetic Theory (eqrly 70’s)
  - Tested empirically for arterials using “chase car” data in Austin, TX (Jones, E., Herman, R., Mahmassani, H., 1988)
Travel Time Reliability

• Model is calibrated and tested at different aggregation levels using different data sources

• Data sources
  – Vehicle trajectories from simulation output
  – GPS probe data (location and time)

• Aggregation levels
  – Network level
  – O-D level
  – Path level
  – Link level
Simulated Trajectory Data

- Models are calibrated for different sizes of networks at different aggregation levels
- Three model forms are tested
  - Linear model
  - Square root model
  - Quadratic model
- Linear model gives best results
- Model parameters are estimated by Weighted Least Square (WLS) to accommodate heteroscedasticity

<table>
<thead>
<tr>
<th>Network</th>
<th>Irvine</th>
<th>CHART</th>
<th>New York City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Zones</td>
<td>61</td>
<td>111</td>
<td>3697</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>326</td>
<td>2182</td>
<td>28406</td>
</tr>
<tr>
<td>Number of Links</td>
<td>626</td>
<td>3387</td>
<td>68490</td>
</tr>
<tr>
<td>Number of Vehicles</td>
<td>58385</td>
<td>151973</td>
<td>6766805</td>
</tr>
<tr>
<td>Demand Duration (hr)</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
Simulated Trajectory Data

- Model comparison – network level analysis

(a) Irvine; (b) CHART; (c) New York City
Simulated Trajectory Data

- Model comparison – path level analysis

(a) Irvine; (b) CHART; (c) New York City
Simulated Trajectory Data

- Model comparison – link level analysis

(a) Irvine; (b) CHART; (c) New York City
Simulated Trajectory Data

- Performance comparison
GPS Probe Data

- Seattle network
  - ~600 zones
  - ~6000 nodes
  - 549,624 trips
  - ~400 participating vehicles
GPS Probe Data

- Seattle network

**Network Level**

**OD Level**

**Path Level**

**Link Level**

- Seavle network
TomTom GPS Trajectory Dataset (Manhattan, NYC)

Preliminary Travel Time Reliability Analysis – O-D Pairs

OD Pair Mean Travel Time (sec/km)

Monday

\[ y = 0.6473x - 31.306 \]
\[ R^2 = 0.7068 \]

Tuesday

\[ y = 0.3498x - 9.3314 \]
\[ R^2 = 0.4652 \]

Wednesday

\[ y = 0.5407x - 21.483 \]
\[ R^2 = 0.6243 \]

Thursday

\[ y = 0.3673x - 11.737 \]
\[ R^2 = 0.6376 \]

Friday

\[ y = 0.4207x - 19.675 \]
\[ R^2 = 0.7206 \]

Source: Delcan, Inc.
Connection between Network Reliability and Network-wide Fundamental Diagram (NFD)
Simulated Networks

- 4 urban networks across the U.S.
- Size varies from 3000 links to 18000 links
- Simulations conducted under three different demand levels
Definitions

- **distance-weighted mean of travel time rate**
  \[ \mu = \frac{\sum_{i=1}^{n} d_i t_i'}{\sum_{i=1}^{n} d_i} = \frac{\sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} d_i} \]

- **distance-weighted standard deviation of travel time rate**
  \[ \sigma = \sqrt{\frac{\sum_{i=1}^{n} d_i (t_i' - \mu)^2}{\sum_{i=1}^{n} d_i}} \]

- **space-mean speed**
  \[ \bar{u}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} t_i} \]

- **network density**
  \[ \bar{k} = \frac{\sum_{j=1}^{m} l_j k_j}{\sum_{j=1}^{m} l_j} \]

- **network flow**
  \[ \bar{q} = \frac{\sum_{j=1}^{m} l_j q_j}{\sum_{j=1}^{m} l_j} \]

where:
- \( i \) = vehicle index
- \( n \) = total number of vehicles
- \( t_i \) = travel time of vehicle \( i \)
- \( d_i \) = travel distance of vehicle \( i \)
- \( t_i' \) = travel time rate of vehicle \( i \), in min/mile
- \( j \) = link index
- \( m \) = total number of links
- \( l_j \) = length of link \( j \)
- \( k_j \) = density of link \( j \), in veh/mile/lane
- \( q_j \) = flow rate of link \( j \), in veh/hour
Relation between Mean Travel Time Rate and its Standard Deviation
Relation between Mean Travel Time Rate and its Standard Deviation

- Linear model:
  \[ \sigma(t') = \theta_1 + \theta_2 \mu(t') \]

- Slope \( (\theta_2) \):
  How fast standard deviation grows with mean travel time rate

- X-intercept \(- \frac{\theta_1}{\theta_2}\):
  Minimum travel time rate (or inverse of maximum space-mean speed)
Existence of NFD

Network flow rate vs. network density

Chicago

Baltimore

Salt Lake City

CHART
Existence of NFD

Speed-density relationship
Connection Between NFD and Travel Time Reliability

Analytical solution

Based on:

i. Linear relationship between mean travel time rate and its standard deviation
\[ \sigma(t') = \theta_1 + \theta_2 \mu(t') \]

ii. NFD
\[ \bar{q} = f(\bar{k}) \]
\[ \bar{u}_s = \left(1 - \frac{k}{k_j}\right) u_f \quad \text{(Greenshields)} \]

- Relationship between standard deviation of travel time rate and network density
\[ \sigma = \theta_1 + \frac{\theta_2 \cdot k_j}{(k_j - k) u_f} \]

- Relationship between standard deviation of travel time rate and network flow rate
\[ q = \frac{\theta_2 \cdot k_j}{(\sigma - \theta_1)} - \frac{\theta_2^2 \cdot k_j}{(\sigma - \theta_1)^2 u_f} \]

- At maximum flow rate (or optimal density)
\[ \sigma = \theta_1 + \frac{2\theta_2}{u_f} \approx -\theta_1 \quad \text{because} \quad \frac{\theta_1}{\theta_2} \approx \frac{1}{u_f} \]
Connection Between NFD and Travel Time Reliability

Travel time variability increases with network density

- **Chicago**
- **Baltimore**
- **Salt Lake City**

**CHART**
Connection Between NFD and Travel Time Reliability

Travel time variability as a function of network flow rate

- **Chicago**
- **Baltimore**
- **Salt Lake City**
- **CHART**
Network Congestion Dynamics: Hysteresis under loading vs. reloading Gridlock formation
Loading vs. Reloading

Reloading follow the same path in the afternoon?
Loading vs. Reloading

Morning

Afternoon
Loading vs. Reloading

- Network Throughput
- Drop

Loading

Reloading

Morning

Afternoon

Q

K
Loading vs. Reloading

- **Q**: Capacity Drop
- **K**: Morning vs. Afternoon
Evidence from Chicago, IL

Average Network Flow (vph) vs. Average Network Occupancy (%)

- Initial Loading
- Reloading
- Initial unloading
- Secondary unloading

August 4, 2009
Evidence from Chicago, IL

First cycle of loading-unloading

Second cycle of loading-unloading

August 4, 2009
Evidence from Portland, OR

Average Network Flow (vph)

Average Network Occupancy (%)

Initial loading
Reloading
Initial unloading
Series4

April 29, 2011
Evidence from Portland, OR

First cycle of loading-unloading

Second cycle of loading-unloading

Average Network Flow (vph)

Average Network Occupancy (%)
Evidence from Minneapolis, MN

Geroliminis and Sun (2011a)
Evidence from Minneapolis, MN

Geroliminis and Sun (2011a)
Evidence from Minneapolis, MN

Geroliminis and Sun (2011b)
证据来自明尼阿波利斯，MN

Geroliminis和Sun (2011b)
Evidence from Chicago, IL (simulation)
Evidence from Chicago, IL (simulation)

Loading Profile

- Initial Loading
- Reloading
Evidence from Chicago, IL (simulation)

Network Fundamental Diagram
Evidence from Chicago, IL (simulation)

Network Fundamental Diagram
Evidence from Chicago, IL (simulation)

Network Fundamental Diagram

![Diagram showing trip completion rate vs. vehicle accumulation with a note on reloading.](image-url)
Network Gridlock
Recovery Hysteresis & Gridlock Formation

![Graph showing vehicle accumulation and cumulative number of vehicles over time.](image)

- **Trip Completion Rate (per 5min)**
  - Gridlock
  - Loading
  - Recovery
  - \( T = 300 \text{ min} \)
  - \( n_g = 166,096 \)

- **Cumulative Number of Vehicles**
  - Generation
  - Out Flow

- **Simulation Time (minute)**
  - 0 to 840

53
Spatio-Temporal Evolution of Gridlock
Gridlock Propagation & Dissipation

- Gridlock Propagation: $y = 3.5321x - 423.46$, $R^2 = 0.9806$
- Gridlock Dissipation: $y = -0.0953x + 629.54$, $R^2 = 0.9453$
Spatio-Temporal Characteristics of Gridlock

- Propagation Duration
- Recovery Duration
- Propagation Speed
- Recovery Speed

![Graph showing Spatio-Temporal Characteristics of Gridlock]

- 100% demand
- 85% demand
- 75% demand

Simulation Time (min): 0 120 240 360 480 600 720 840

Number of jammed links: 0 200 400 600 800 1000

- Gridlock Formation
- Gridlock Propagation
- Gridlock Dissipation

- 125 min
- 300 min
Implications and Applications

• Robust relation between Sd. Deviation and mean of trip time per unit distance:
  – Signature for given network: where we may be on curve depends on overall demand levels, and traffic controls
  – Seek better understanding of factors that affect the shape of these relations
• Expand realm of network-wide traffic theories to include reliability.
• Allows incorporating reliability performance indicators in objective set for control interventions.
• Practical approaches to obtain reliability measures to incorporate in economic evaluation of capital and operational interventions.
• Major application to date of Sd. Dev. Relation to mean at O-D and path level: generate route level reliability indicators in reliability-aware network traffic assignment (SHRP2 Project C04; Jiang et al., 2011).
• Reliance on trajectories allows ready extension to other modes, non-motorized, etc...
• New era of trajectory-driven traffic and network performance analysis.