Quantifying City-Scale Resilience to Extreme Congestion Events

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Joint work with Brian Donovan (UIUC) & Dr. Jong Lee (NCSA)

[Research Sponsors: NSF, NCSA, FHWA RSI UTC, IDOT]

[Open source code and data available at GitHub and publish.illinois.edu/dbwork]

Goal: Empirically quantify resilience to extreme congestion events

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- Extreme congestion events characterized by:
  - Changes in travel demand
  - Loss of cyber components
  - Damage to physical components
- Assess transportation network performance quantitatively
  - Recovery time
  - Deviation deviations from typical conditions

Gasoline shortages after Hurricane Sandy

[A. Savulich, New York Daily News, 2012]

Go to "war" with the sensors you have, not the ones you want – D. Estrin

- 697,000,000 taxi trips (2010-2013)
- FOIL data: New York City Taxi and Limo Commission
- Data structure:
  - Only two GPS points
    - Start of trip
    - End of trip
  - Meter distance and travel time
  - Driver ID and Car ID
  - Fare data
  - **Download:** publish.illinois.edu/dbwork/open-data

Filtering the data

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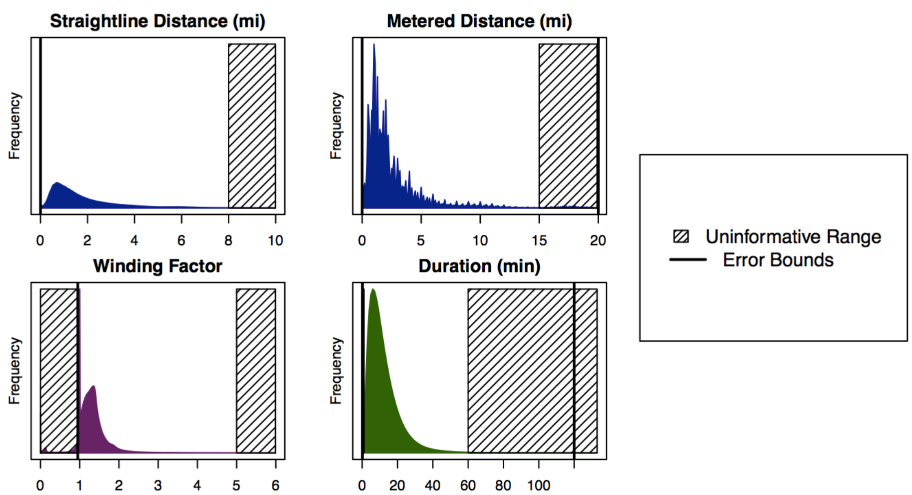

(7.5% data errors, 11% uninformative)

High resolution traffic estimation with coarse GPS data

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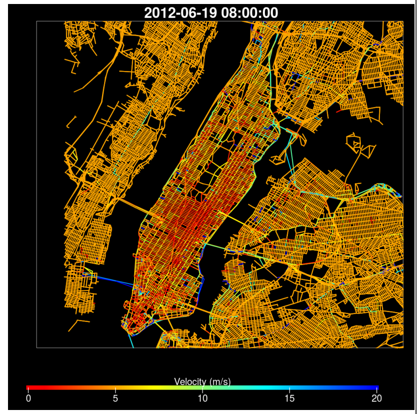
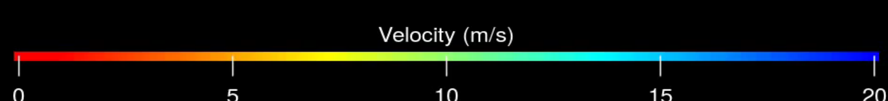
- Compute hourly traffic paces via iterative link travel time estimator
  - Routing: Given link speeds, route all taxis and compute predicted travel times
  - Link travel time correction: Compare predicted travel times with true travel times, then adjust the link travel times to minimize the travel time prediction error



[Donovan, Lee, Work, *IEEE T-ITS,* 2016 (in review); Santi et al. *PNAS* 2014]

Over many iterations…



Scaling to multi-year datasets

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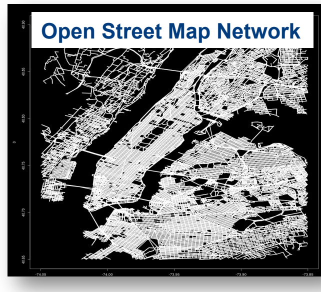
- NYC road graph
  - 24,000 nodes
  - 63,000 links
- Typical hour: 20,000 trips
- Computing traffic estimates
  - Bottleneck: routing step
  - Accuracy: ~2 min error per trip
  - Saved estimates: publish.illinois.edu/dbwork/open-data



Storing traffic data in a vector

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- Build a column vector of traffic paces
- Each element corresponds to the average pace in a given hour during the four year period

$$M_1 = \begin{bmatrix} M_{11} \\ M_{21} \\ \vdots \\ M_{m1} \end{bmatrix}$$

Pace on link 1 (Wed noon-1pm, 1/6/2010)

Pace on link 2 (Wed noon-1pm, 1/6/2010)

.
.
.

Pace on link m (Wed noon-1pm, 1/6/2010)

[Donovan, Lee, Work, *IEEE T-ITS 2016* (in review)]

Building a traffic data matrix

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- n = 52 (weeks/year) x 4 (years) copies of traffic on a Wednesday from noon-1pm over a four year period

Wed noon-1pm, 1/6/2010 — Wed noon-1pm, 1/13/2010 — Wed noon-1pm, 12/25/2013

$$M = \begin{bmatrix} M_{11} & M_{12} & \cdots & M_{1n} \\ M_{21} & M_{22} & & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{m1} & M_{m2} & \cdots & M_{mn} \end{bmatrix}$$

[Donovan, Lee, Work, *IEEE T-ITS 2016* (in review)]

Facts about traffic data matrices

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- If traffic is perfectly periodic and repeatable:
  - all columns of M are identical
  - M is a rank 1 matrix

Wed noon-1pm, 1/6/2010 — Wed noon-1pm, 1/13/2010 — Wed noon-1pm, 12/25/2013

$$M = \begin{bmatrix} M_{11} & M_{12} & \cdots & M_{1n} \\ M_{21} & M_{22} & & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{m1} & M_{m2} & \cdots & M_{mn} \end{bmatrix}$$

- Real traffic matrices
  - Have missing data
  - Have estimation errors
  - Have some columns that are far from typical (e.g., 12/25/2013 is a federal holiday)

[Donovan, Lee, Work, *IEEE T-ITS 2016* (in review)]

Detecting outliers via Robust PCA

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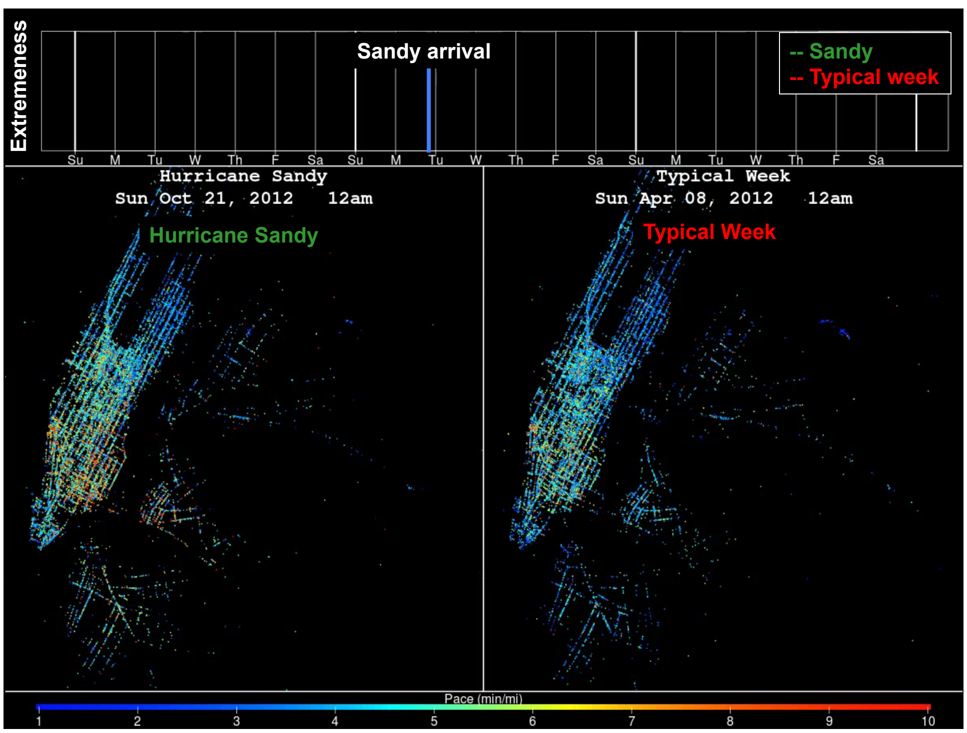
- *Problem:* Given Data Matrix M, find a decomposition composed of:
  - M: original data matrix
  - L: low rank matrix
  - C: column sparse matrix indicating outliers
- Solved via convex optimization:

$$\text{Minimize:} \quad \|L\|_* + \lambda \|C\|_{1,2}$$
$$\text{Subject to:} \quad \|M - (L + C)\|_F \leq \varepsilon$$

- **Key outcome:** Any nonzero column in C is an outlier
- Extreme points in the low dimensional subspace are also identified as outliers via Mahalanobis distance.

[Xu, Caramanis, and Sanghavi, *IEEE Trans Information Theory,* 2012; Donovan, Lee, Work, *IEEE T-ITS 2016* (in review)]



Worst events for New York City traffic

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Event	Start Time	Duration (Hours)	Max Pace Dev (Min/Mi)	Min Pace Dev (Min / Mi)
Hurricane Sandy	2012-10-28 21:00	134	2.26	-1.54
Snowpocalypse	2010-12-26 13:00	109	4.24	0.33
Blizzard	2011-01-31 10:00	47	2.01	0.34
Hurricane Irene	2011-08-27 13:00	43	0.65	-1.65
Blizzard	2010-02-10 06:00	32	0.65	-1.03
Blizzard	2013-02-08 06:00	27	1.53	-0.59

Summary and future perspectives

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- Quantifying extreme events
  - Hurricane Sandy: ~5 days of recovery time
  - *Worst congestion after* the hurricane hit.
  - Re-entry process is significantly slower than evacuation.

- *Long term goal:* Improve transportation policy

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