PEER Transportation Systems Research Program (TSRP)

City-scale multi-infrastructure network resilience simulation

Kenichi Soga, Bingyu Zhao, Miki Komatsu,
Krishna Kumar, Millard McElwee, Renjie Wu

UC Berkeley, University of Cambridge

in collaboration with
Profs. Jack Baker, Alex Bayen and Joan Walker

PEER

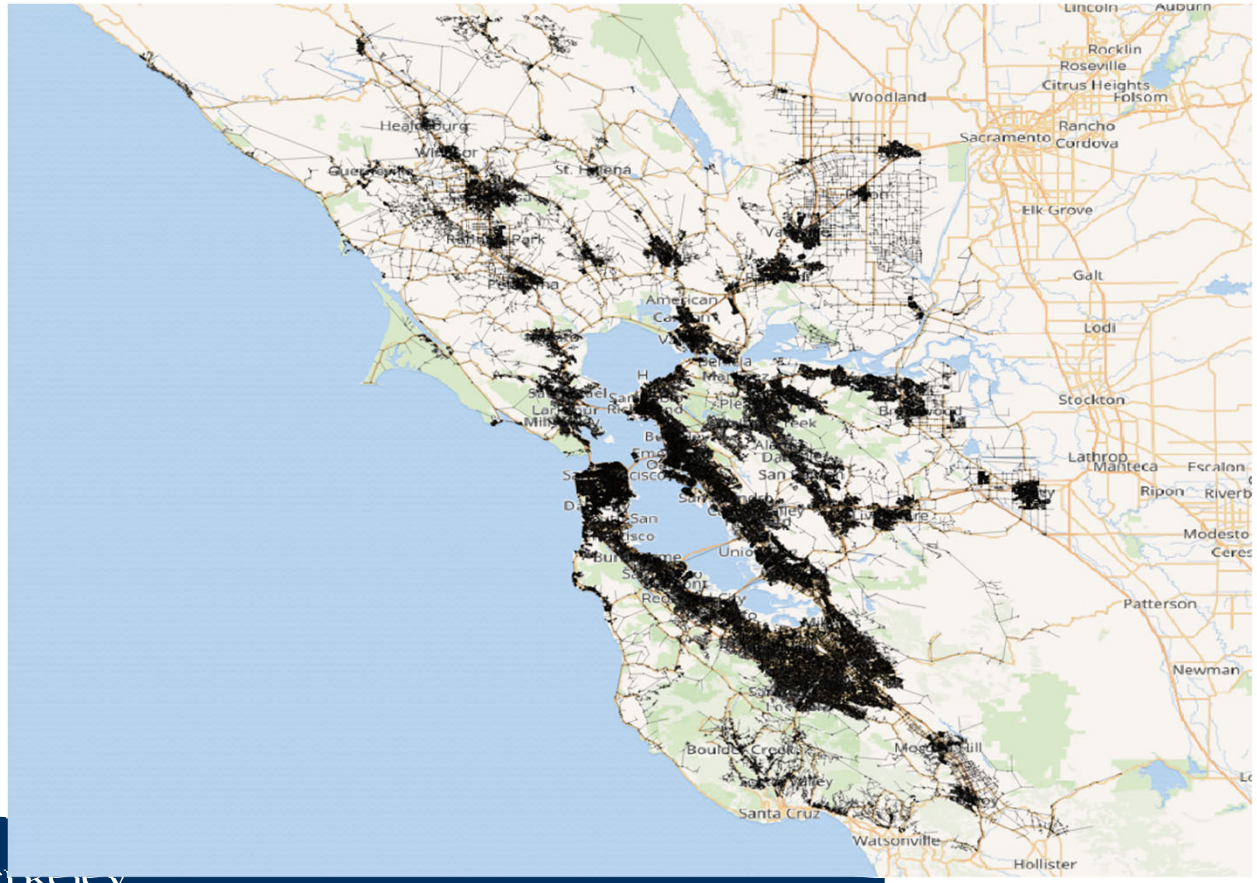
Berkeley
UNIVERSITY OF CALIFORNIA

Camp fire: evacuation and rescue

Berkeley
UNIVERSITY OF CALIFORNIA

The Guardian, KABC.

Bay Area road network

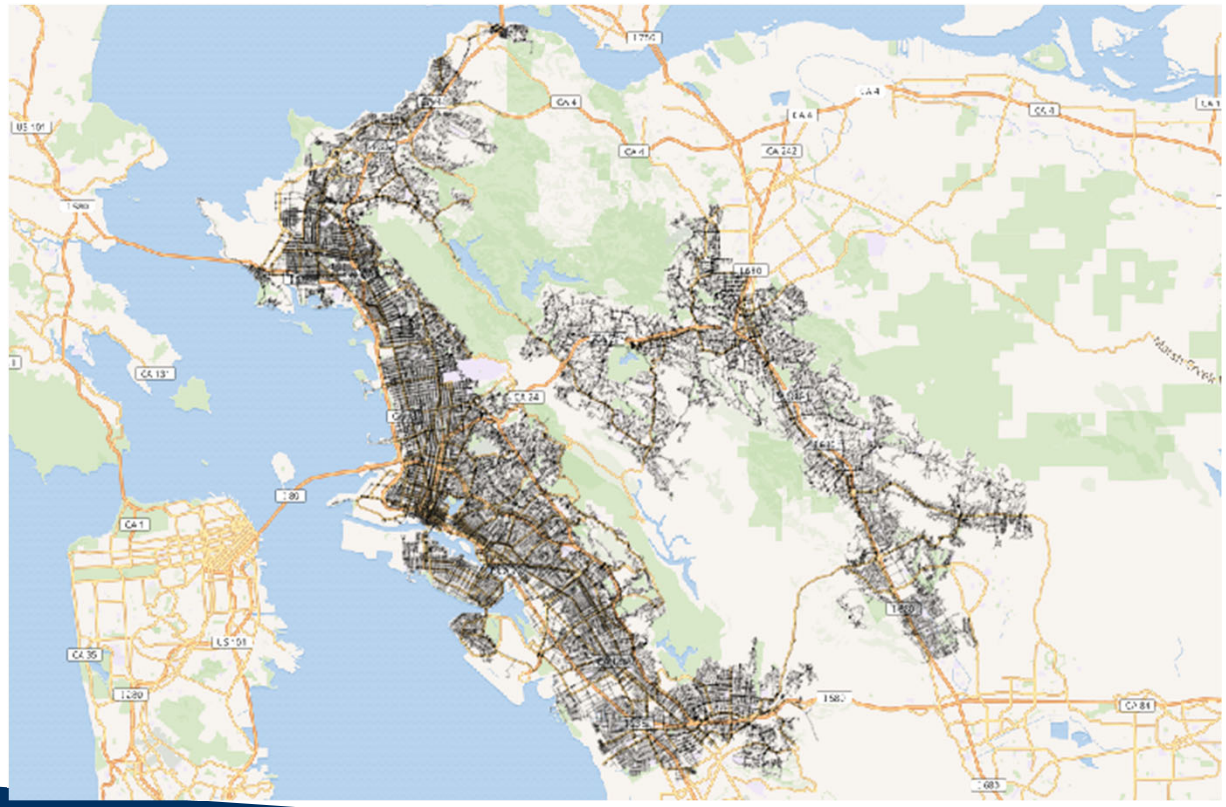


Network size:

224,223 nodes

549,008 edges

EBMUD water pipeline network



Network size:

99,418 pipe joints

108,676 pipes

Berkeley
UNIVERSITY OF CALIFORNIA

Road map

Traffic simulation tool → SimCenter:

- Fast agent routing with priority-queue based Dijkstra algorithm;
- Parallelized & scalable agent-based traffic simulation on HPC.

Hydraulic simulation tool → SimCenter:

- Instantaneously solving hydraulic equations with conjugate gradient solver;
- Explore water supply and serviceability change under different scenarios.

Multi-layered coupled graph analysis tool → SimCenter:

- Understanding the impact and the interactions between different infrastructure networks in a city.

1. Physical conservation of vehicle flow

$$\frac{\partial(Density)}{\partial t} + \frac{\partial(Flow)}{\partial x} = 0$$

Individual vehicles

Individual decisions

Macroscopic fluid-dynamic	Macroscopic agent-based
	Microscopic car-following, queue-based

1st order: v ← headway

2nd order: a ← headway & v

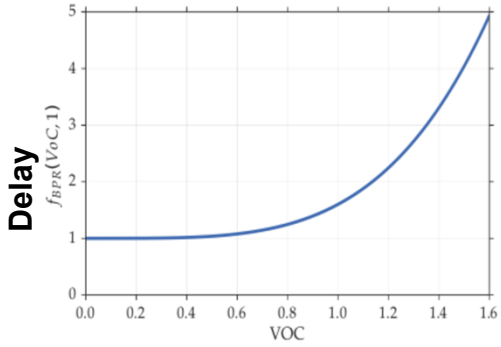
Model lane-changing behavior

2. Empirical rule of velocity/acceleration

1st order: v ← density (volume-delay curves)

2nd order: consider inertia

Easy to calibrate with field measurements

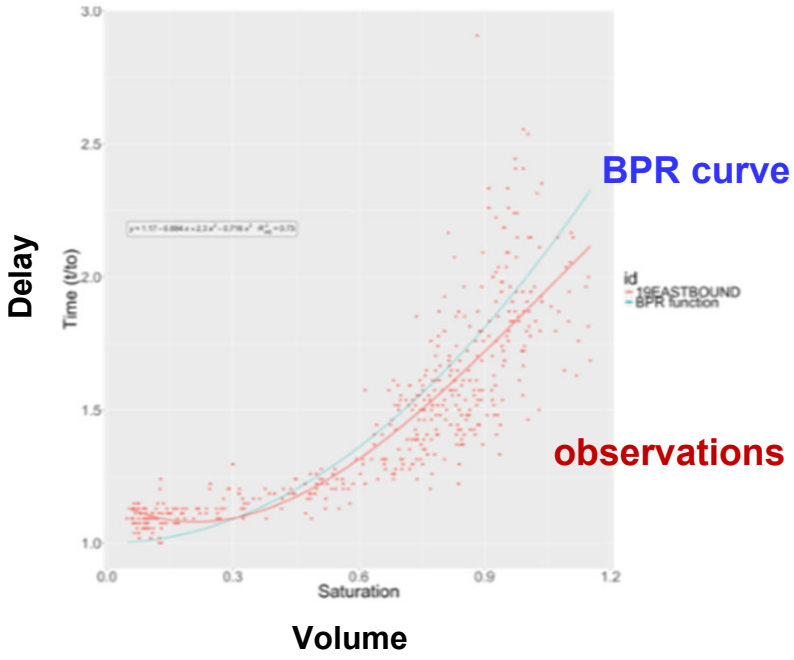


Volume

BPR curve, 1964 & reproduced by Çolak, et al., 2016

Berkeley
UNIVERSITY OF CALIFORNIA

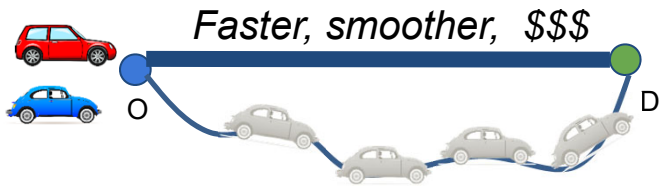
Empirical rule on driving behavior



Casey, 2018

Physical conservation of vehicles

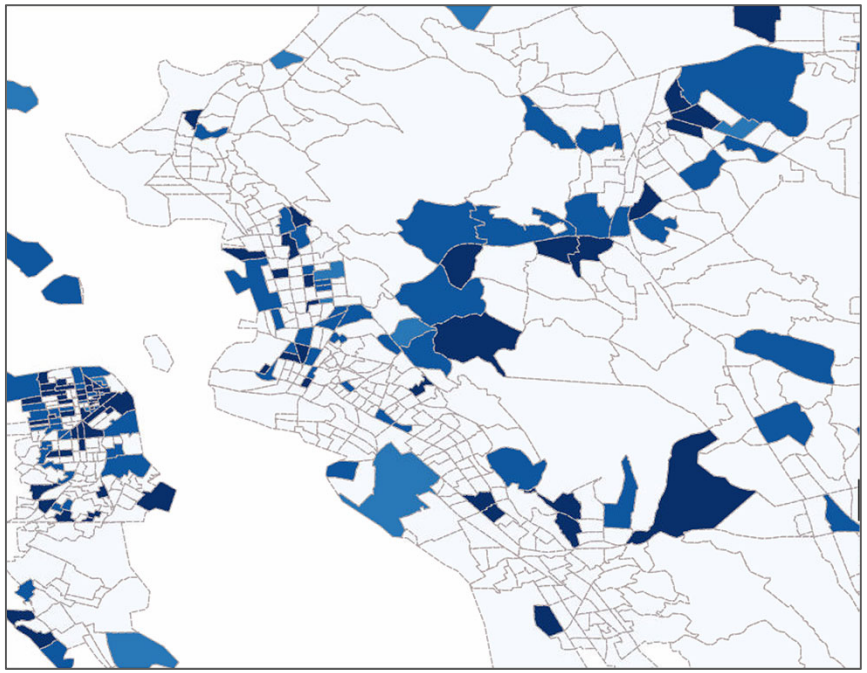
Tracing individual vehicles



Slower, noisier, $

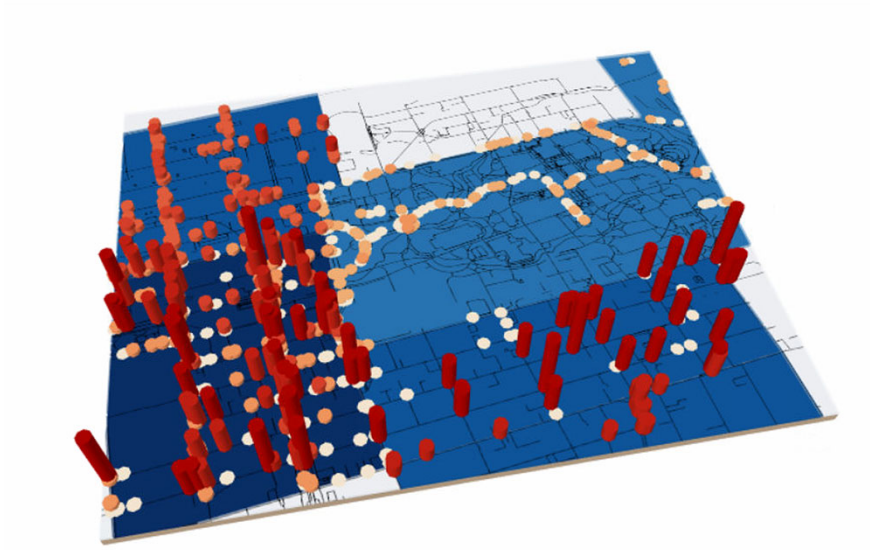
- Decision-oriented heterogeneous users.
- Highway vs residential roads.
- Prioritizing emergency vehicles in disaster scenarios.

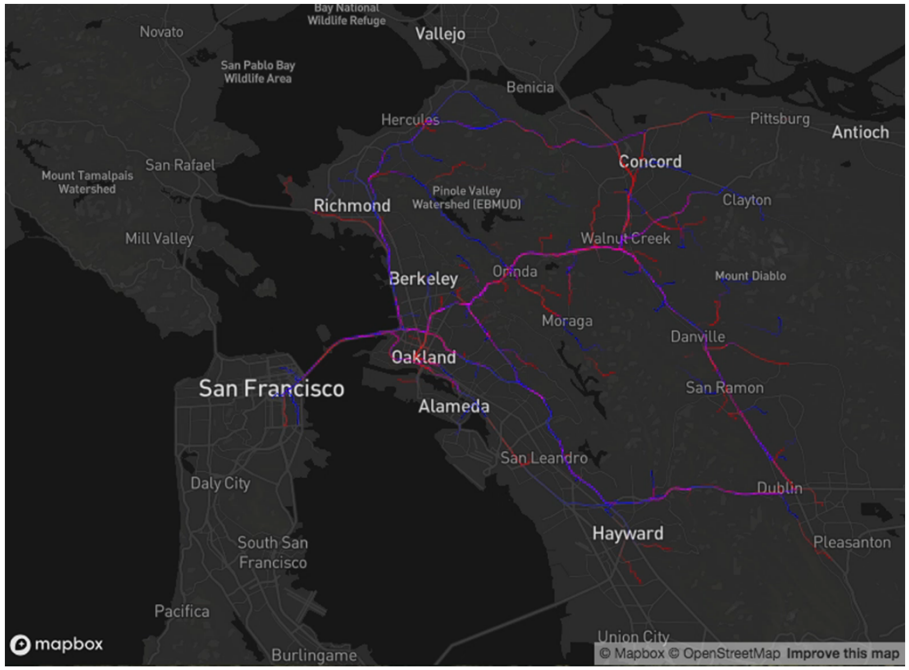
Bay Area road network: travel demand

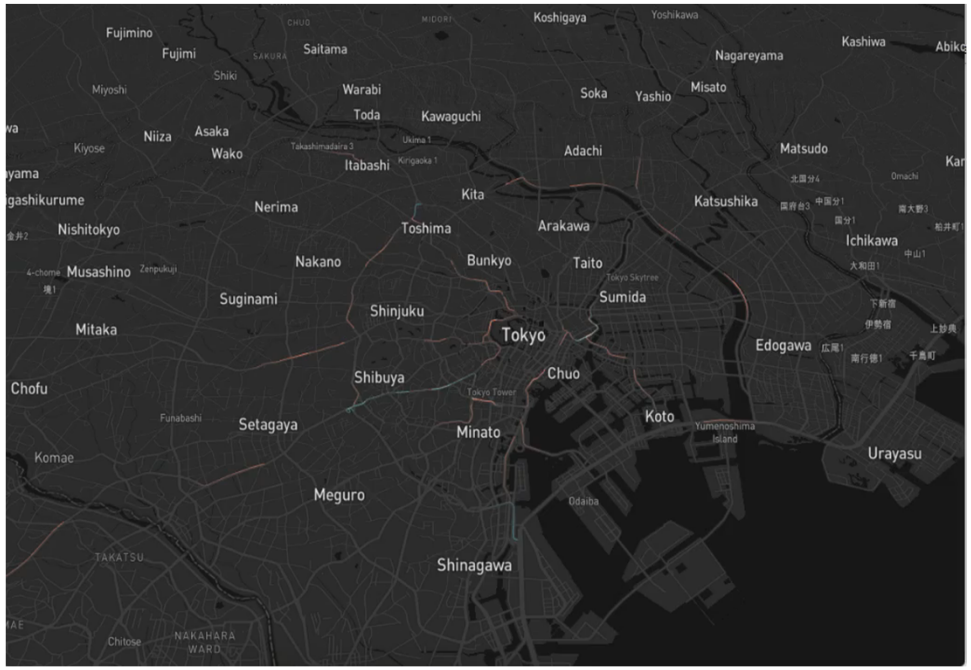


Trips originated from each census tract at 9am on Thursday

Travel demand calculated from the California Household Travel Survey (CHTS) 2010

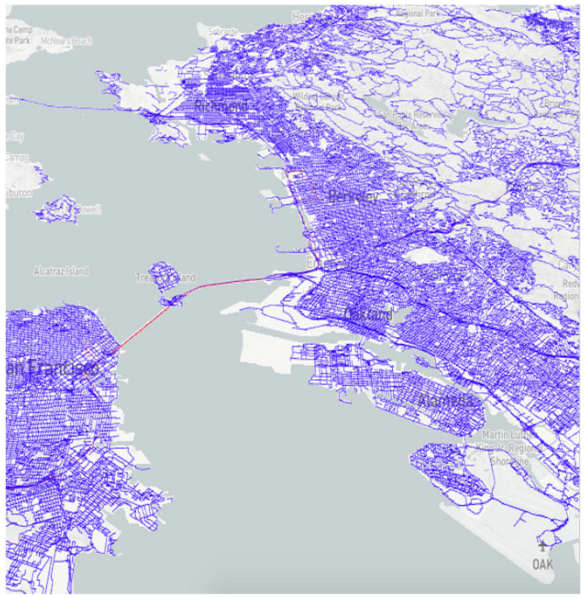




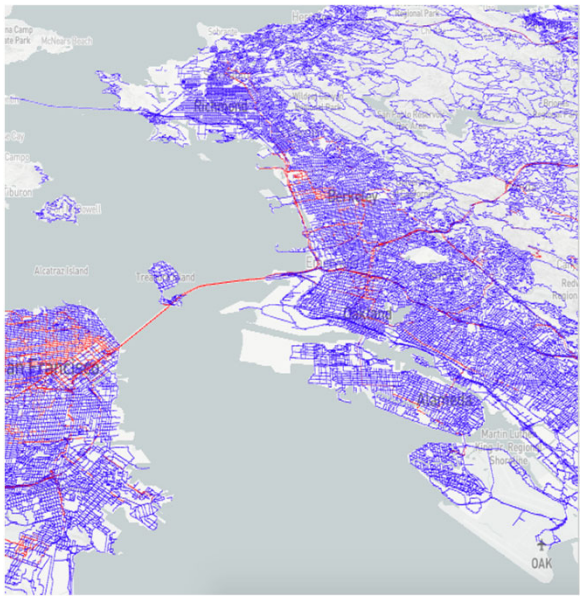


Berkeley
UNIVERSITY OF CALIFORNIA

Bay Area road network: traffic simulations



50,000 agents

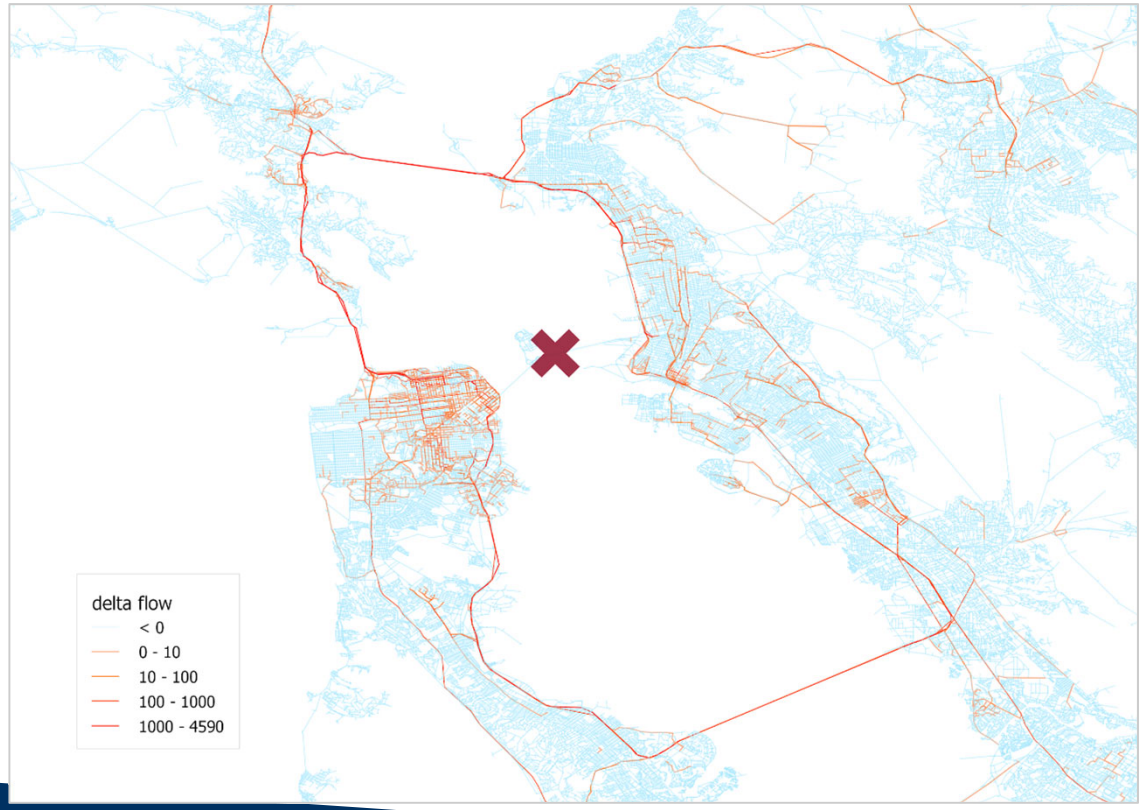


1,000,000 agents

Traffic Flow

based on Thursday 9am demand

Traffic simulation: bridge closure scenario

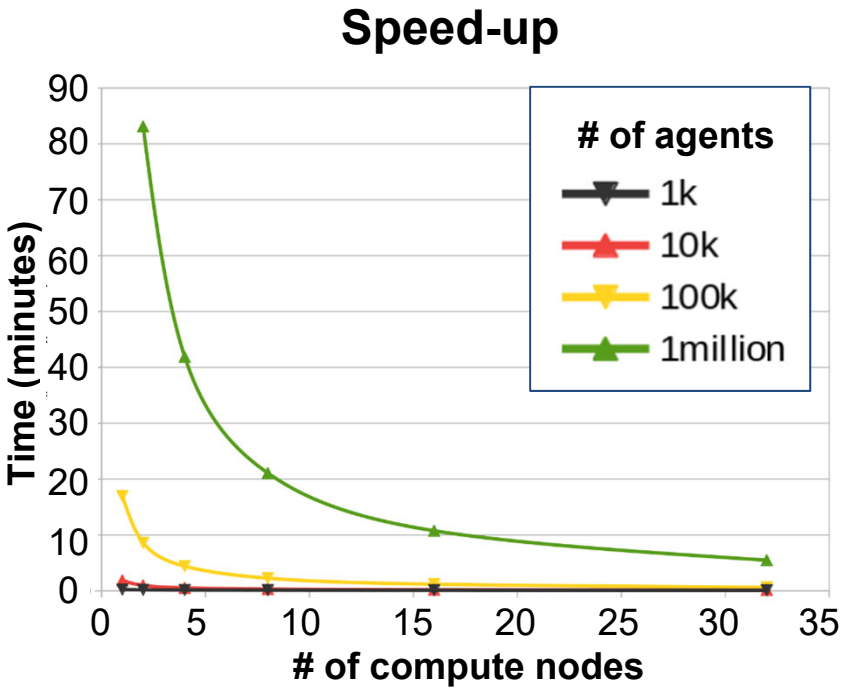


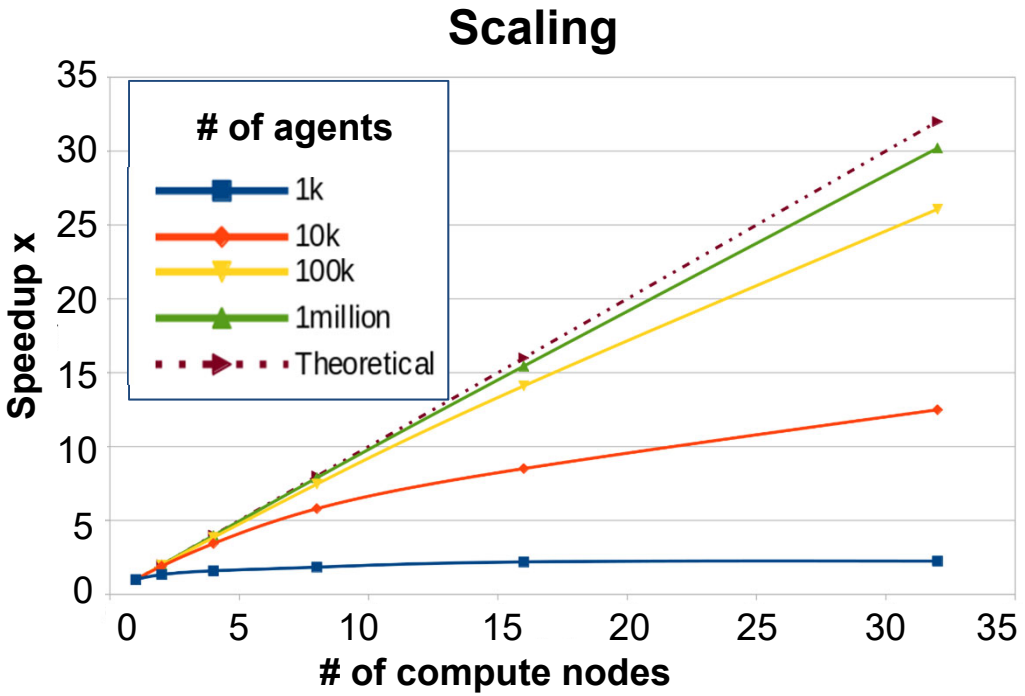
Increased Traffic Flow

after the Bay Bridge is closed

based on Thursday 7am demand
with 325,346 agents

Bay Area road network: traffic simulation speed

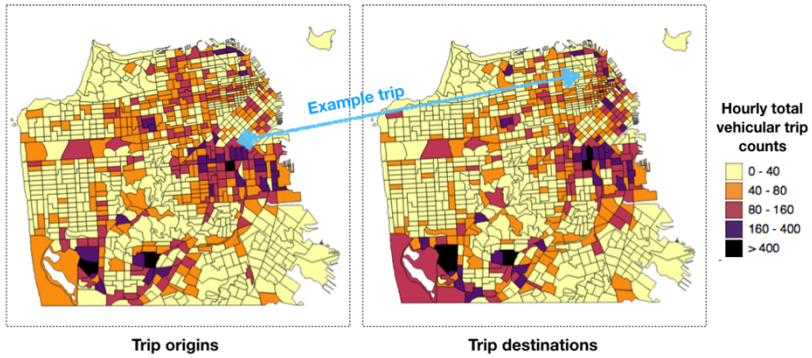




Bay Area road network: traffic simulation speed

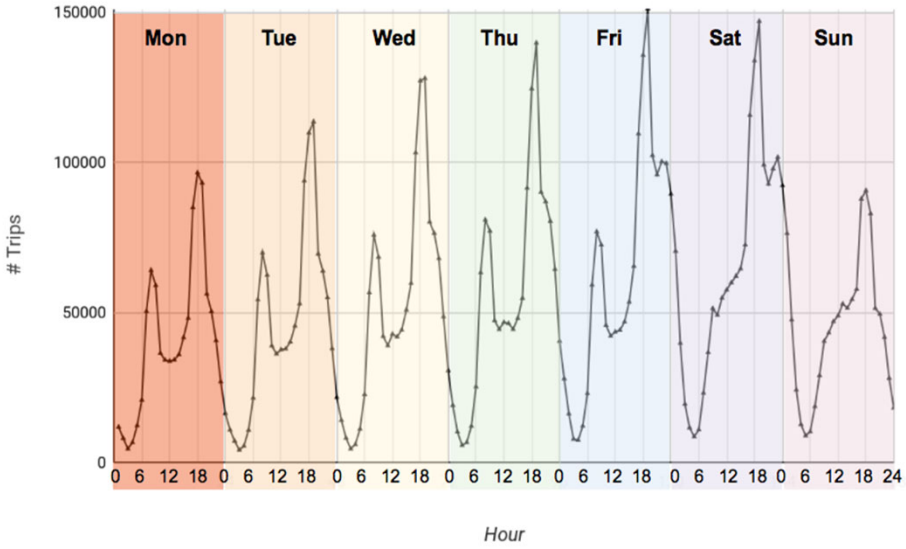
	Processor	# OD pairs	Graph size	Time	Notes
1	GPU	100 million	10k nodes 4m edges	10 seconds	Floyd-Warshall algorithm. Graph size limited by GPU Memory.
2	CPU (32 threads shared memory)	1.26 million (18% bay area population)	Bay Area: 220k nodes 550k edges	10 minutes	Priority-queue based Dijkstra algorithm.
3	MPI+CPU (1024 threads)	1 million (15% bay area population)	Bay Area: 800k nodes 2m edges	~ 5 minutes	"Stress test" showing the performance of our priority-queue based Dijkstra implementation

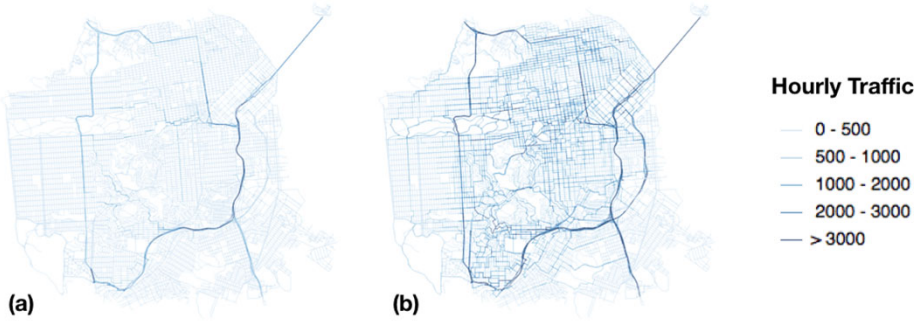
Our shortest path implementation is available at
github.com/cb-cities/sp, github.com/cb-cities/abm



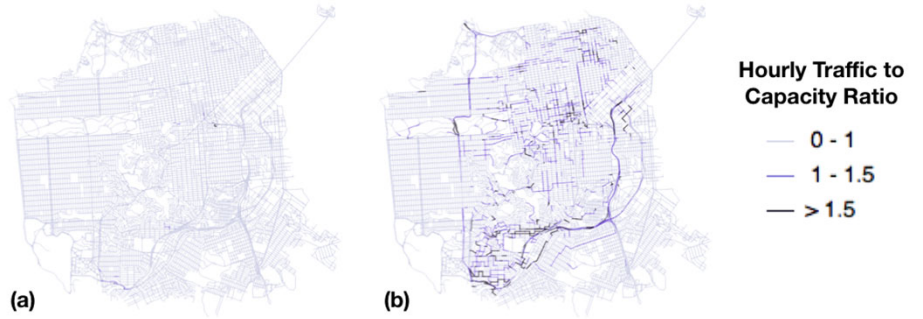
Generating zone-to-zone travel demand through sampling for a typical Monday at 9 AM based on probability defined by zonal-level counts

The number of Uber/Lyft pickups (left) and dropoffs (right) on a typical Monday, 9am

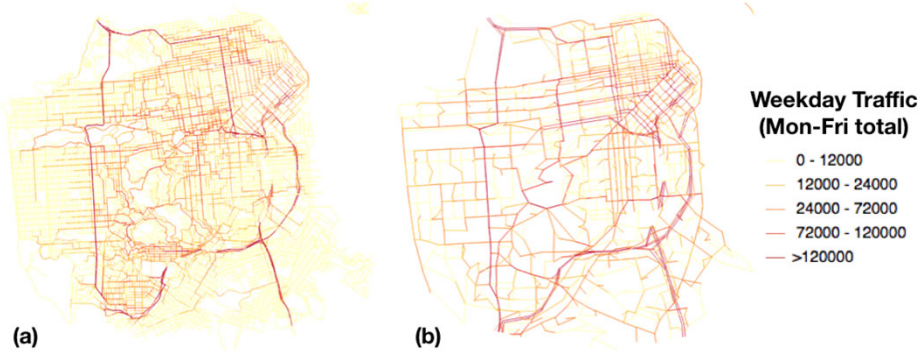




Hourly link-level traffic volume: (a) on a typical Friday at 6 AM; (b) on a typical Friday at 6 PM.

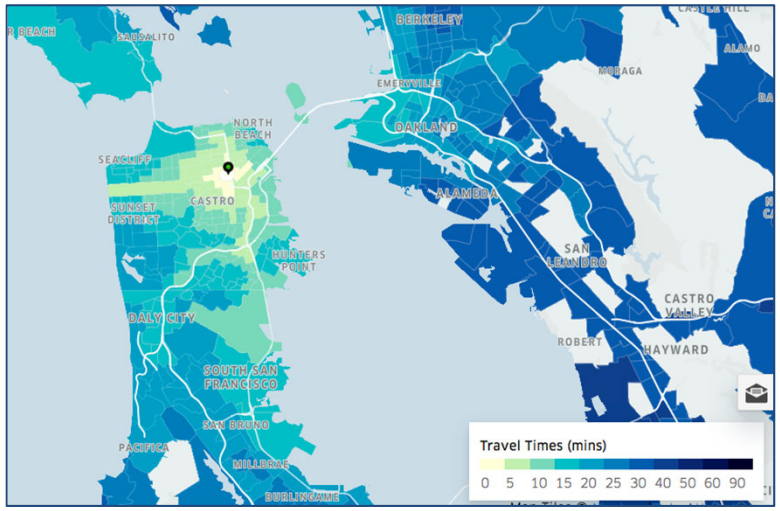


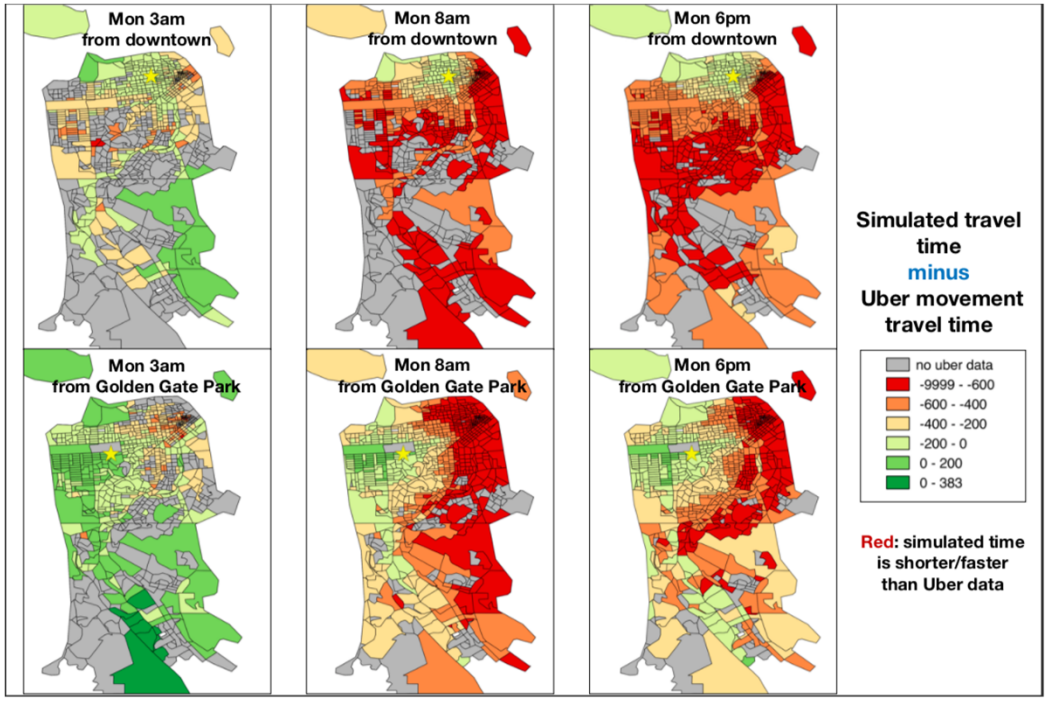
Road volume-to-capacity ratio: (a) on a typical Friday at 6 AM; (b) on a typical Friday at 6 PM.



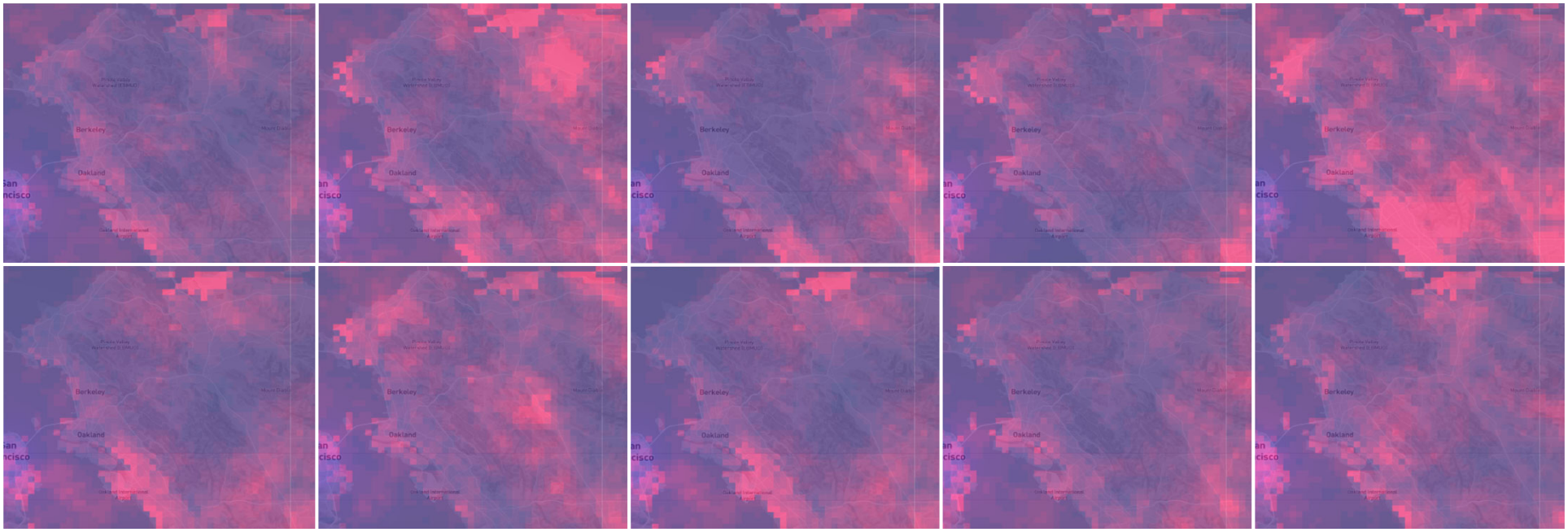
Total simulated traffic in SF from Monday to Friday: (a) results from this study; (b) results from MTC's Travel Model One.

Validation: benchmark data from Uber



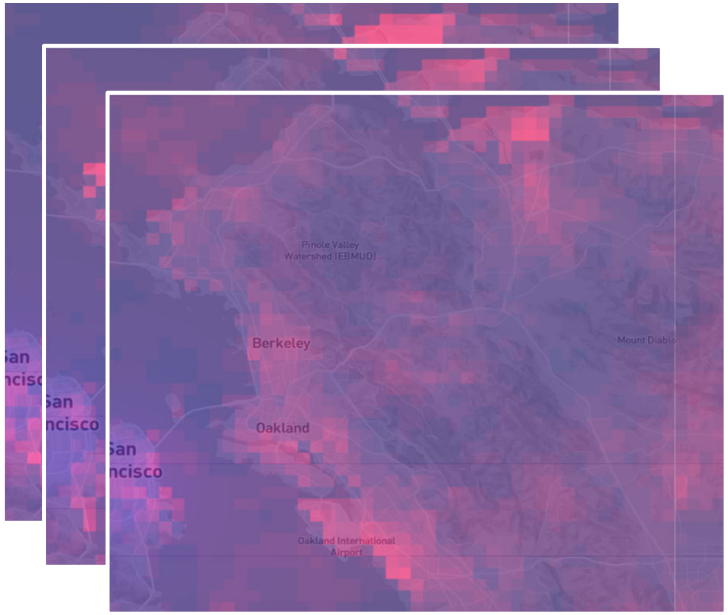


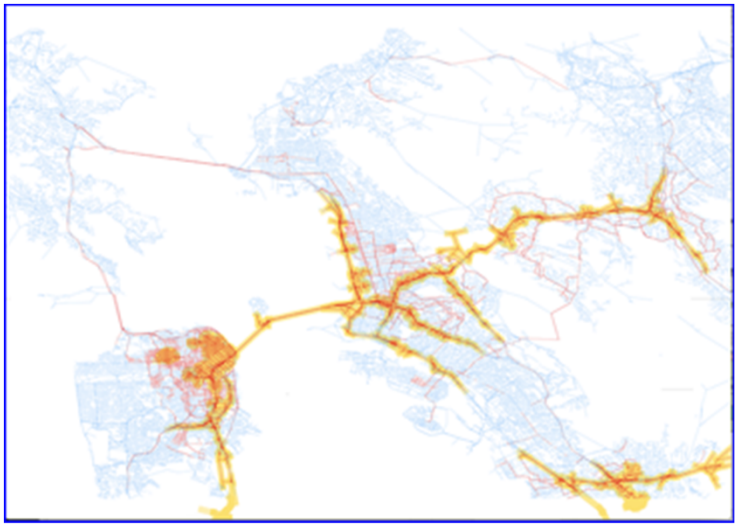
Ground movement scenarios



Professor Jack Baker, Stanford University

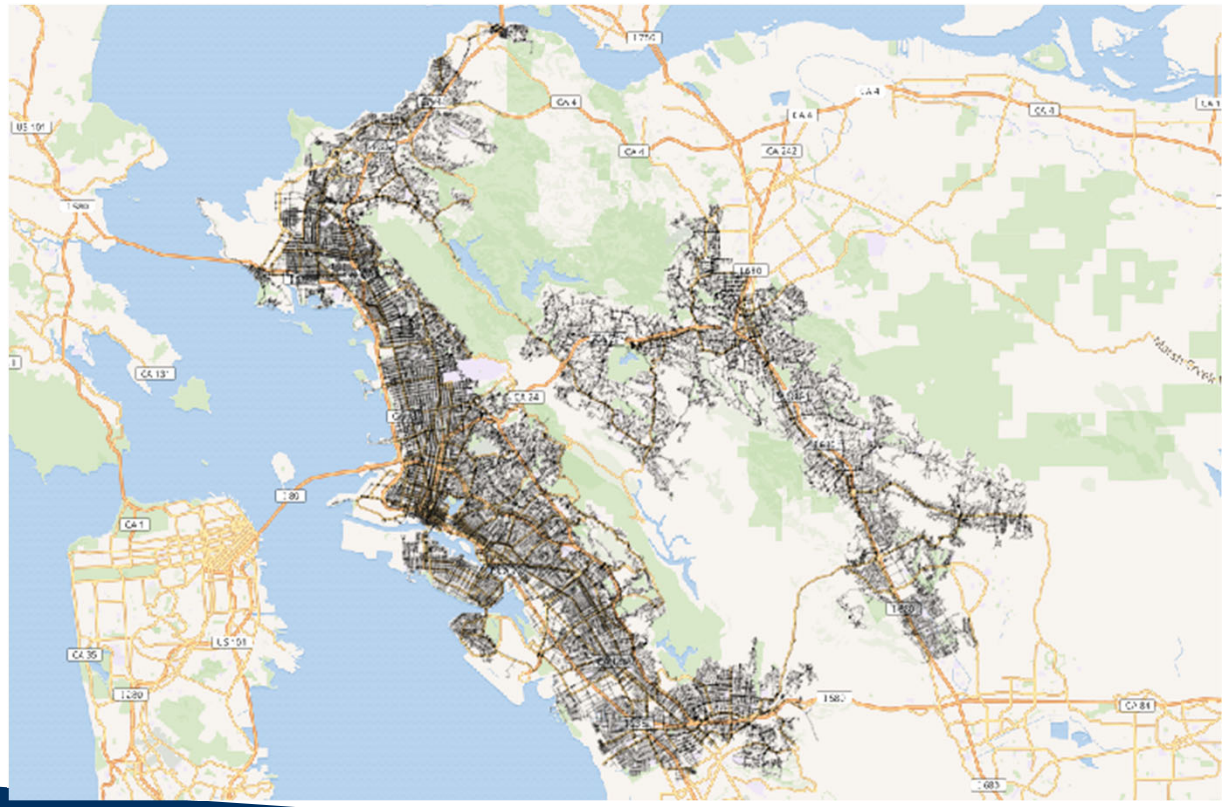
Quantifying seismic resilience





Ground movement intensity scenarios
Professor Jack Baker, Stanford University

EBMUD water pipeline network



Network size:

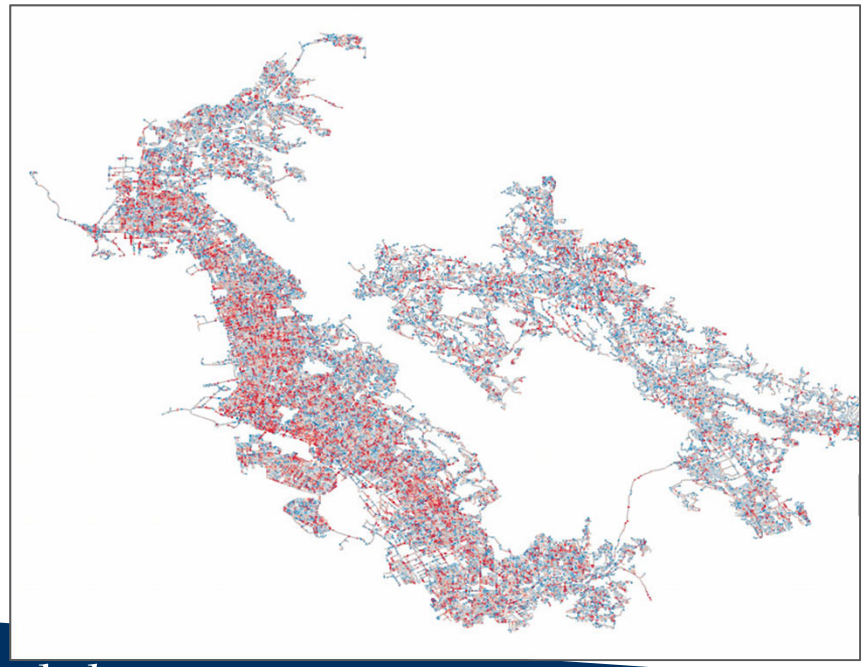
99,418 pipe joints

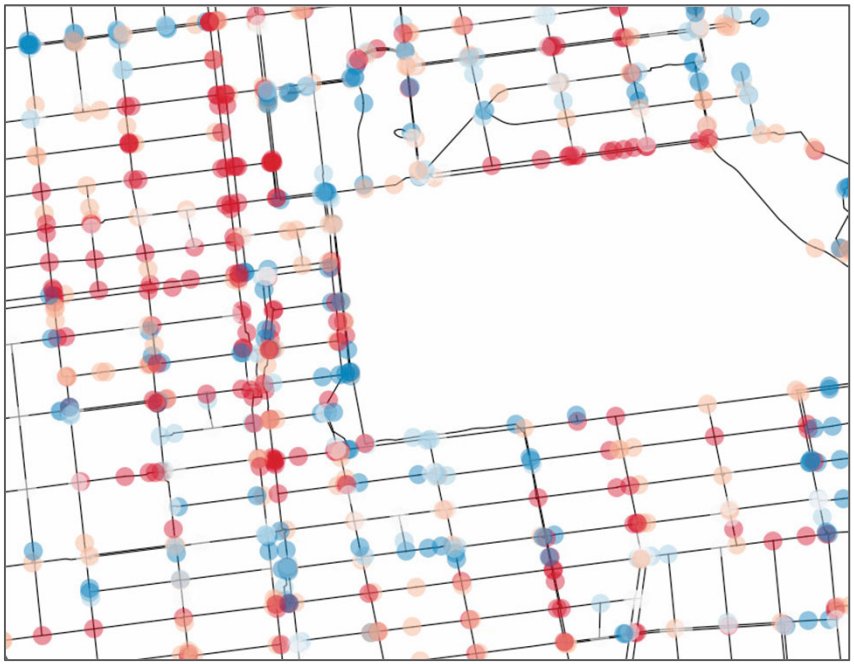
108,676 pipes

Berkeley
UNIVERSITY OF CALIFORNIA

Topological interactions:

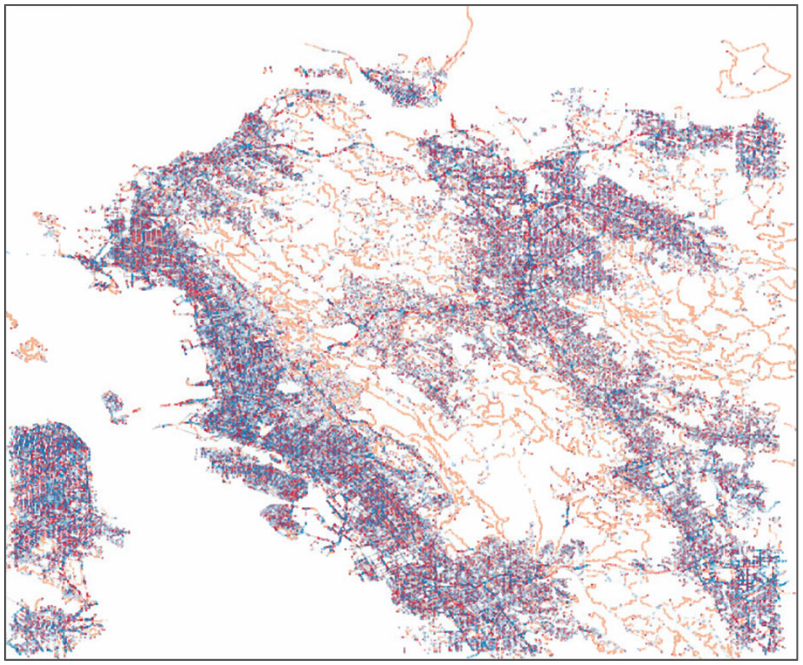
(1) PageRank of the water pipeline network

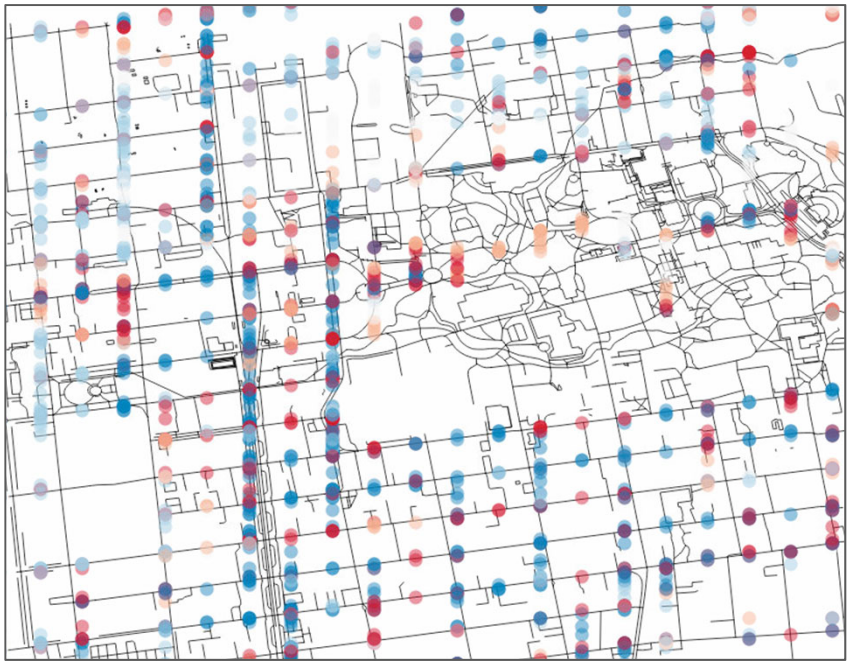




Topological interactions:

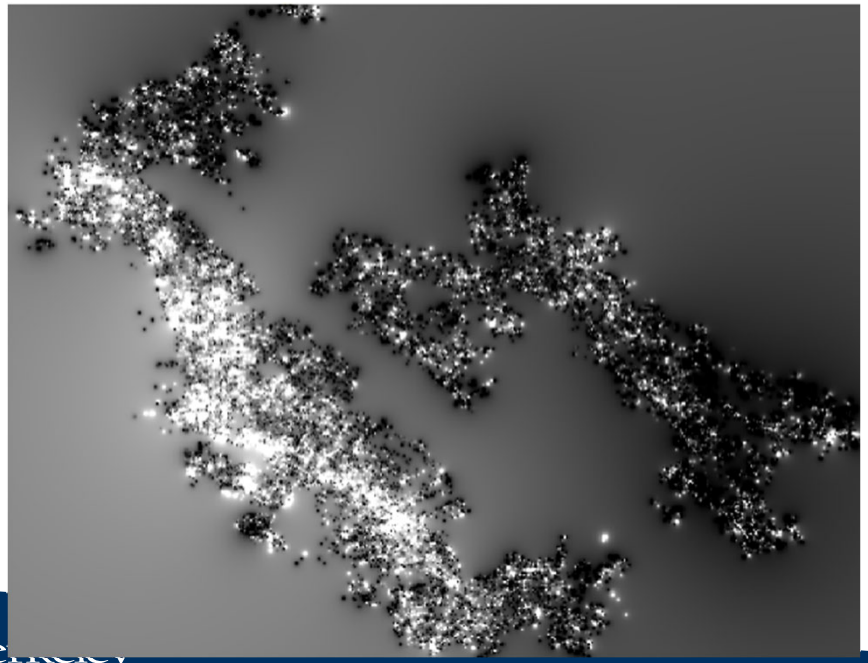
(2) PageRank of the road network

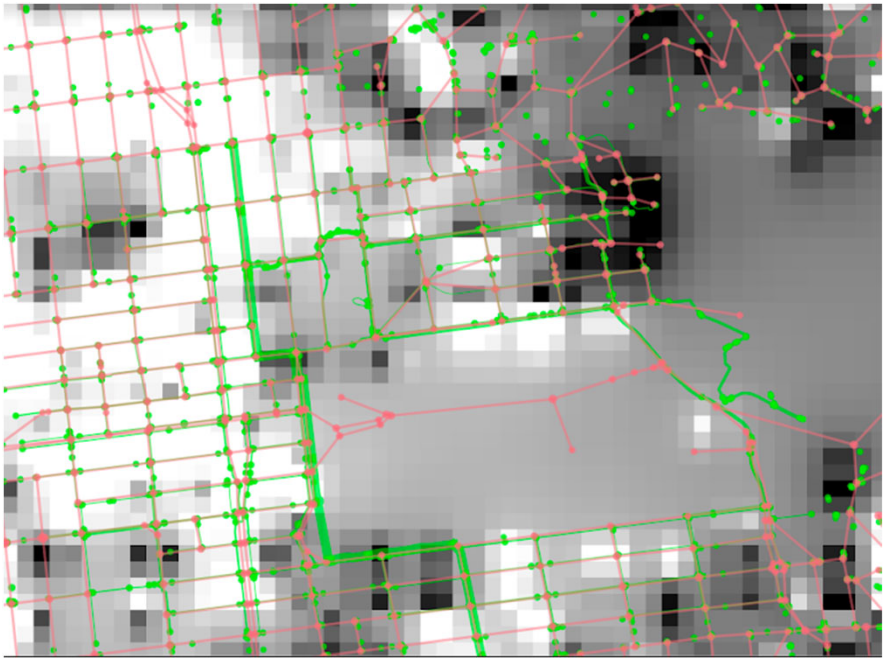




Topological interactions:

(3) Average PageRank: where important road intersections meet important pipe joints.





Code features and computational time

Features

- C++11 with CPU/XeonPhi and GPU support
- Efficient fast pipe GPU-based network solver for city-scale network (1 million nodes)
- Preconditioned Conjugate Gradient solver with both unknown heads and discharge
- Estimate flooding area on pipe break
- Snapshot hydraulic analysis
- Parallel large-data store for analysis and data retrieval

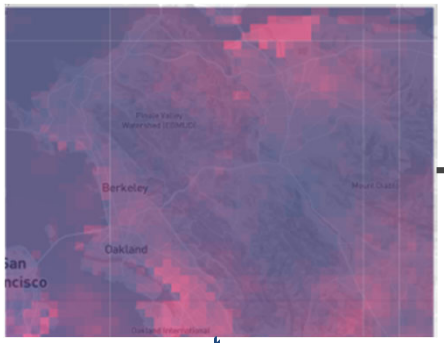
Typical time taken to run a snapshot for a network of 100k and 1 million nodes.

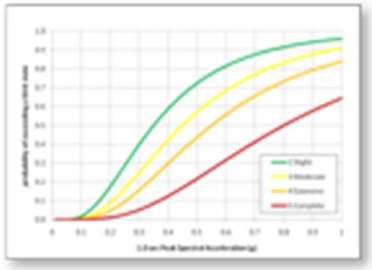
Task	Time (s) 100k	Time (s) 1 million
Network properties	2	3 - 4
Whole Matrix assembler	3	10
Preconditioner + Solver (GPU)	4	6 - 8
Writing DB file and visualisation	3	5 - 10
Update properties	2 - 3	5
Total seconds	15 - 20	30 - 40

Comparison with EPANET

Features	EPANET	CB-Cities
City-scale network (> 1 million nodes)	✗	✓
Snapshot hydraulic analysis	✓	✓
Display network and show parameters on the map	✓	✓
Water quality, reaction and energy analysis	✓	✗
Compute graph properties of the network	✗	✓
Real-time interactive visualisation in a browser	✗	✓
Solve both Known / Unknown Heads / Discharge	✗	✓
Matrix solving algorithm	Todini and Pilati (1987)	Modified CG

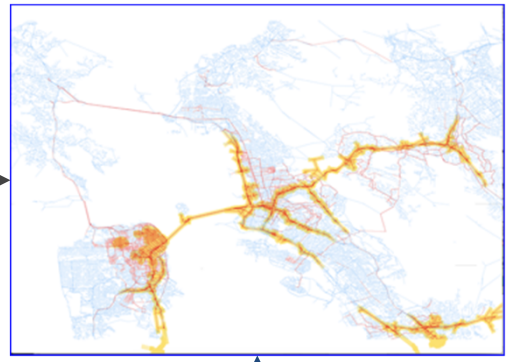
Earthquake scenario generation



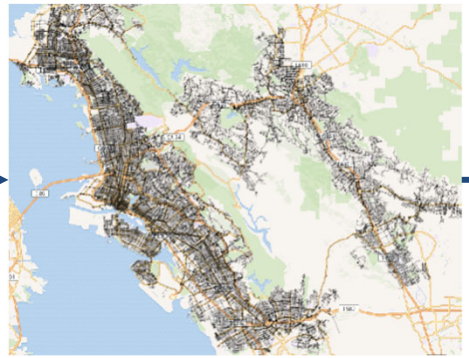


Component (e.g., bridge) damage → reduced road capacity

Traffic simulations



Pipe damage



Hydraulic simulations

Flooding, maintenance closures → reduced road capacity

Thank you.

Berkeley
UNIVERSITY OF CALIFORNIA

CB-Cities HPC Pipe-network Code Structure