Seismic risk to transportation networks: user impacts and at-risk communities

Jack W. Baker

Thanks to Mahalia Miller, Samuel Cortes, Nirmal Jayaram, Maryia Markhvida, Dave Ory, Tom Shantz and Jason Wu

Image from U.S. Geological Survey

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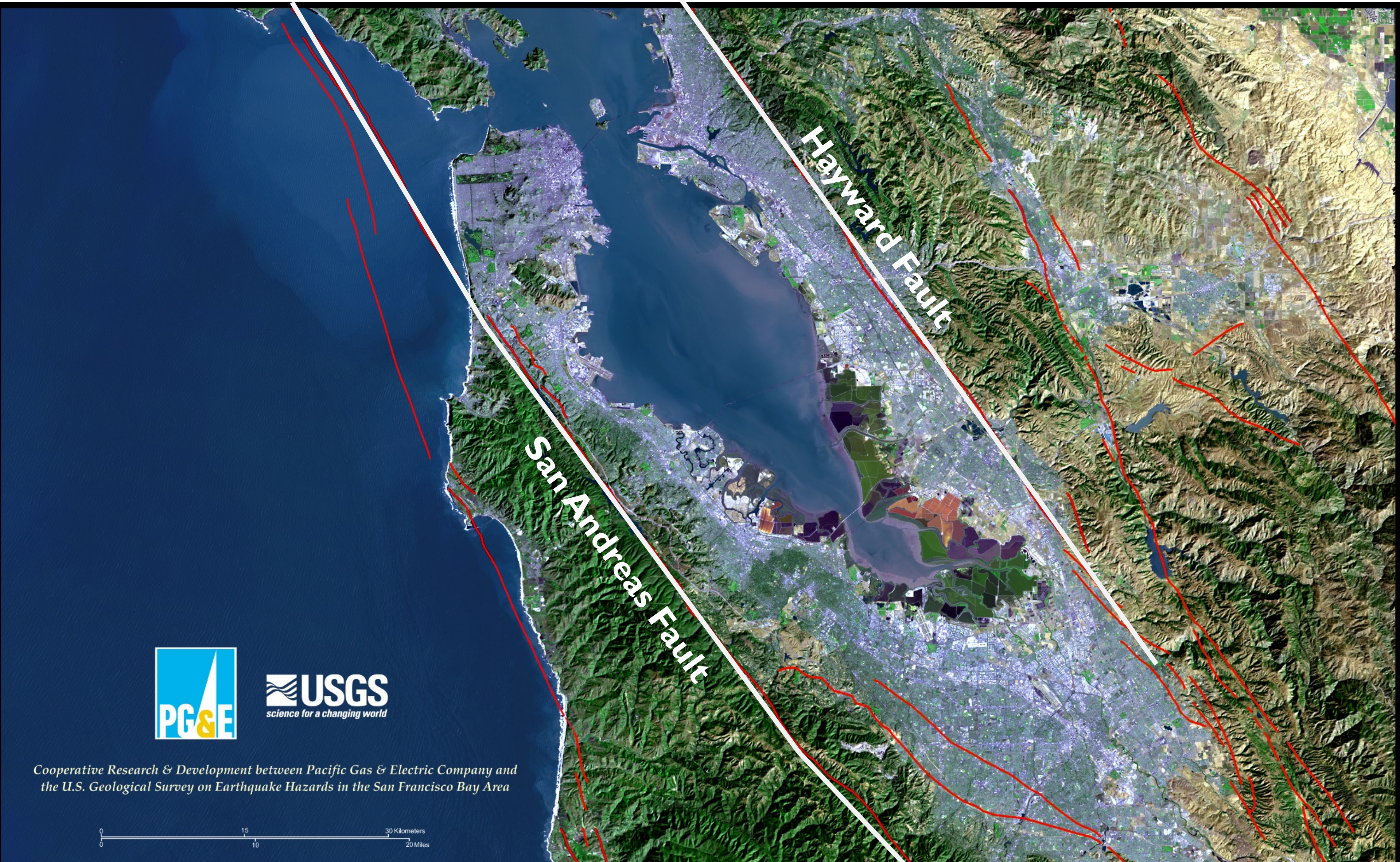
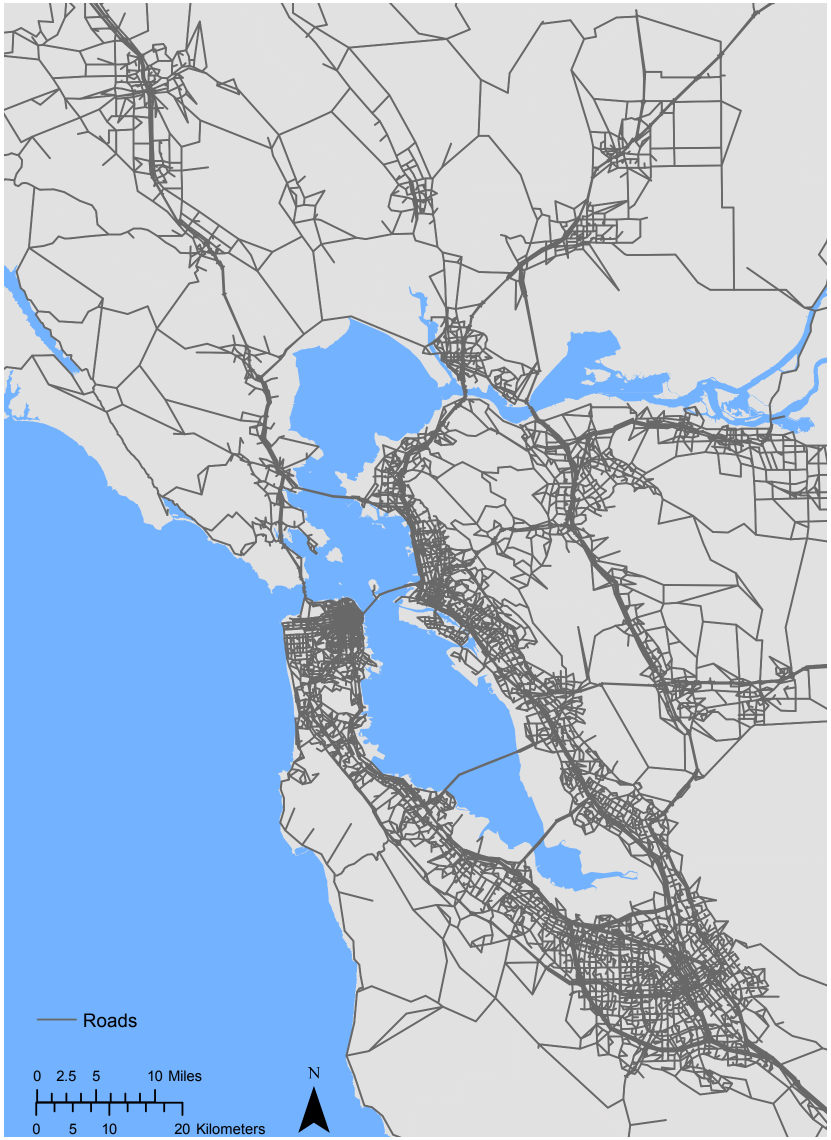
Case study: San Francisco Bay Area transportation system



The transportation model: roads

Road network

- 32,858 road segments
- 20 million trips per day



The transportation model: rail

Road network

32,858 road segments

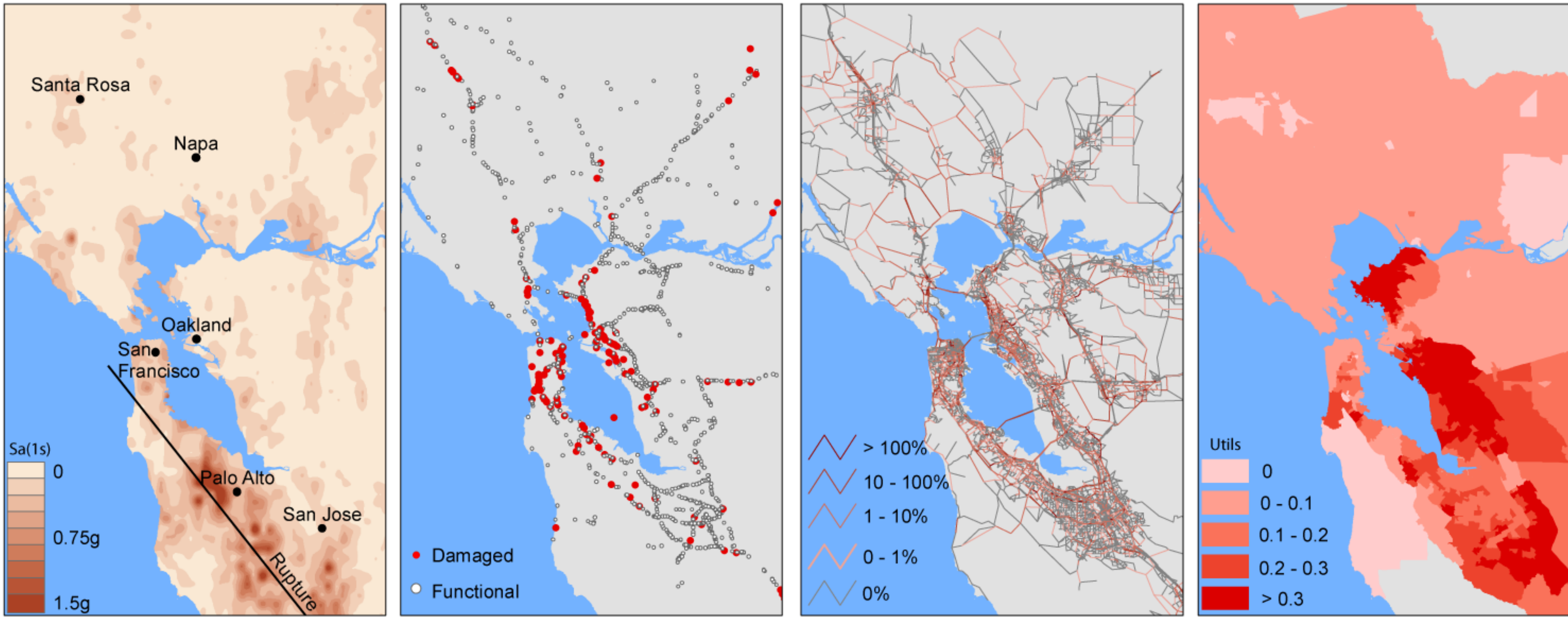
20 million trips per day

Other transit (walk, bike, rail, ferry, bus)

43 additional modes

4 million trips per day

Performance-based assessment: four analysis stages



Step 1: Ground-motion intensity

Step 2: Component damage

Step 3: Network performance

Step 4: User impacts

Step 1a: Earthquake ruptures

Uniform California Earthquake Rupture Forecast, v2 (Field et al., 2009)

- All earthquake sources in the region
- Magnitudes discretized in units of 0.1 (5.0, 5.1, 5.2, …)
- Locations randomized

2800 earthquake ruptures, each with an annual rate of occurrence

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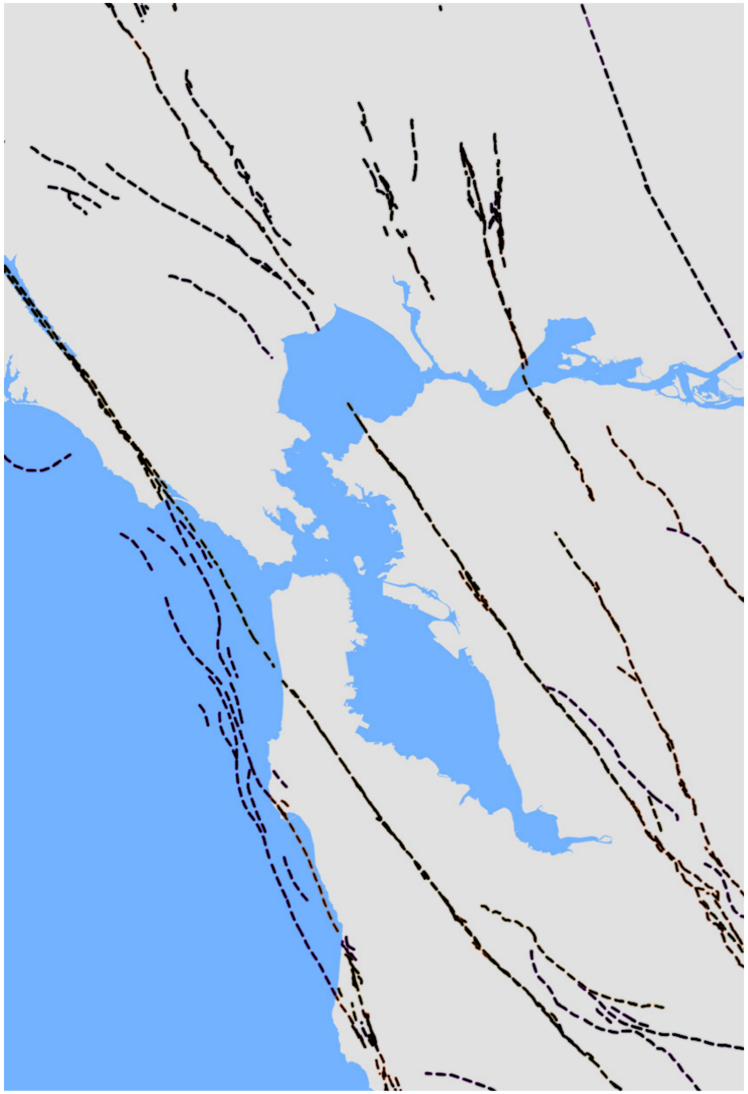
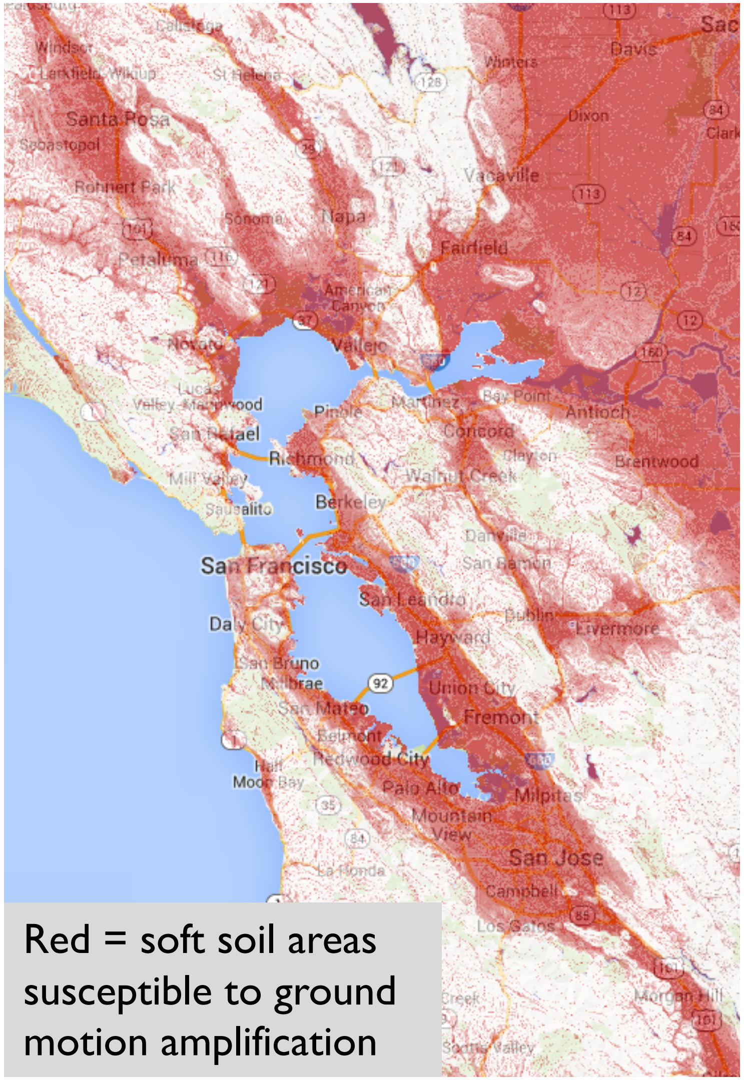


Step 1b: Site conditions

Average shear wave velocity in the top 30m is used to characterize site conditions

Values are inferred from topographic slope (Wald and Allen, 2007)



Red = soft soil areas susceptible to ground motion amplification

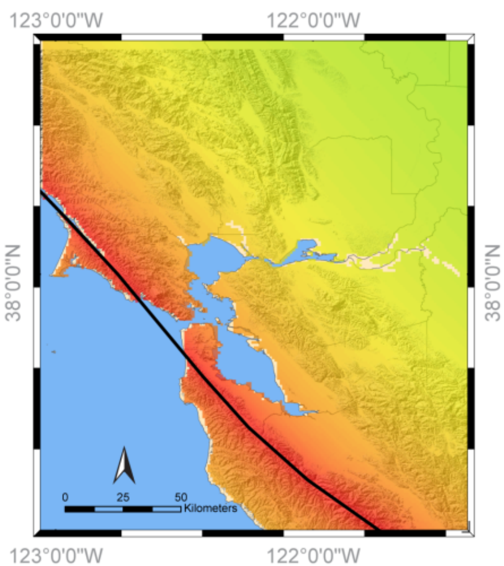
Step 1c: Ground motion prediction

Median and standard deviation of ground motion amplitude, given
- Magnitude
- Source-to-site distance
- Site conditions

Spatially correlated amplitude variability

Simulated ground motion amplitude

Measured here using spectral acceleration at 1 second [*Sa(1s)*]



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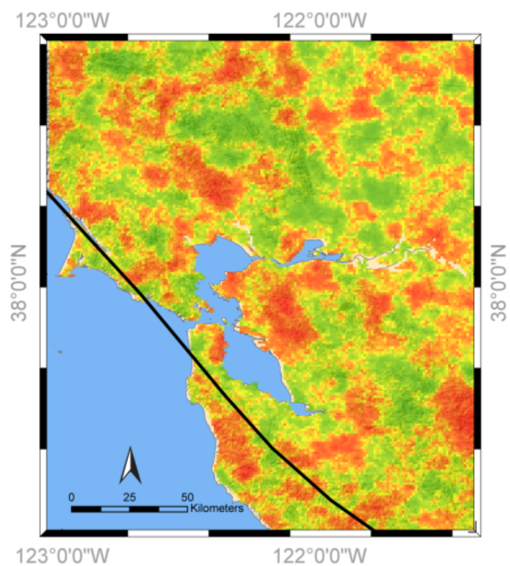

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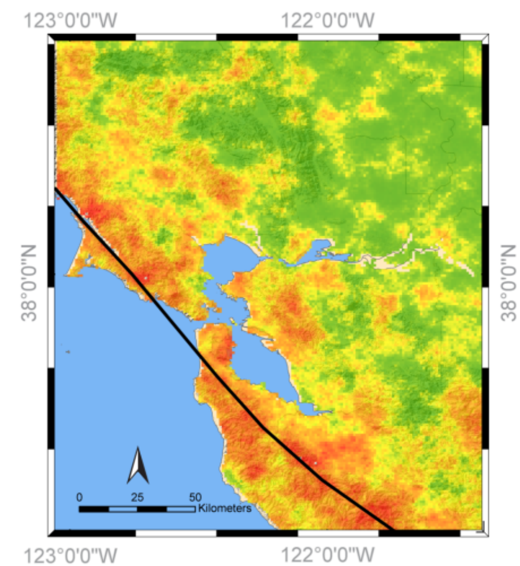

Software to perform Step 1 is available at *www.stanford.edu/~bakerjw/infrastructure.html*

Jayaram and Baker (2010). "Efficient sampling and data reduction techniques for probabilistic seismic lifeline risk assessment." *Earthquake Engineering & Structural Dynamics*, 39, 1109–1131.

Step 2: Component damage

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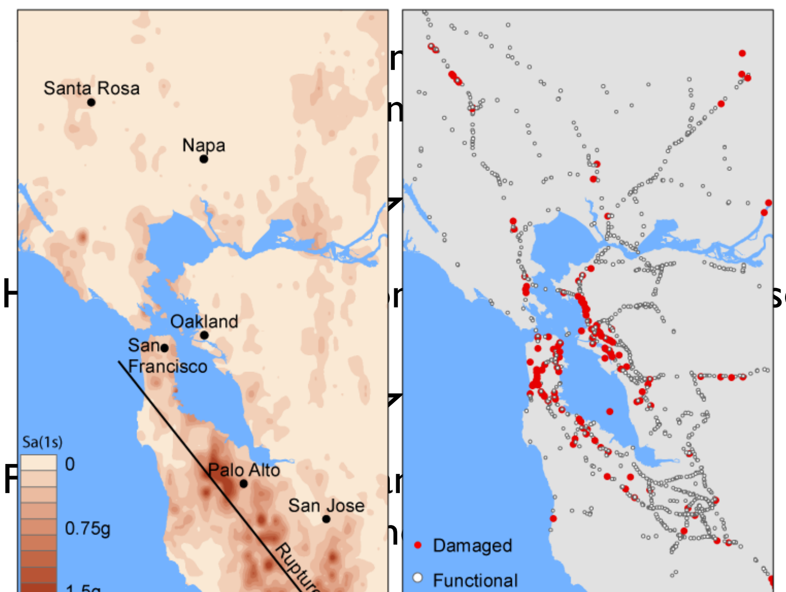
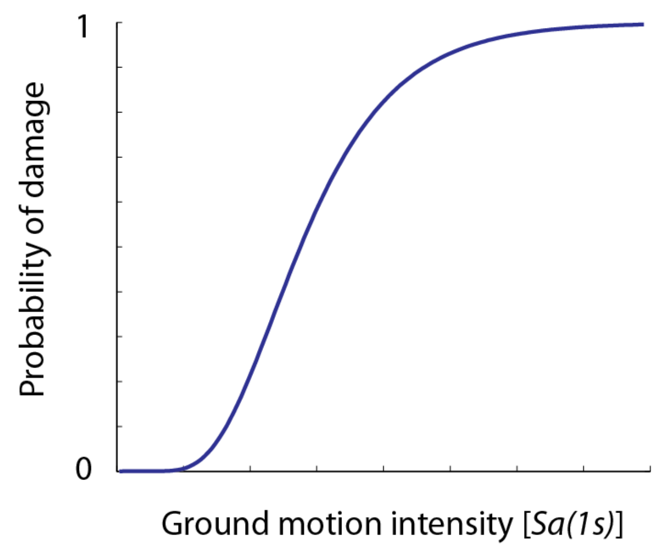




Consider network interdependencies

Through field surveys and aerial photograph studies, we identified overpasses whose closure would also necessitate closing under-passes

From Google Maps

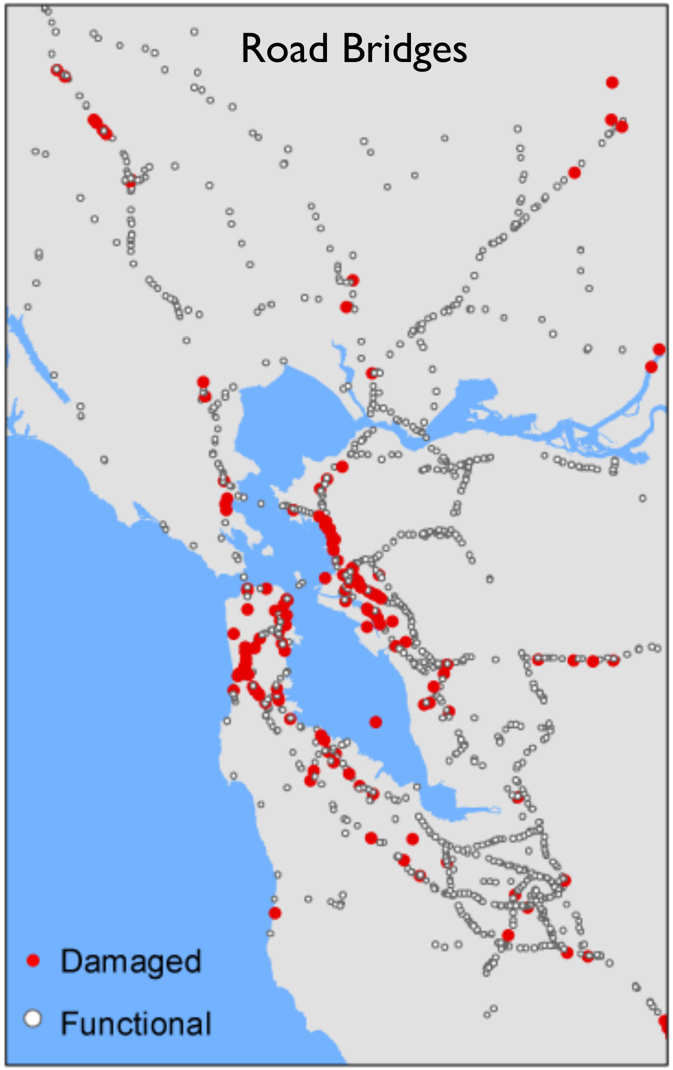
Step 2: Component damage

1743 road bridges

1409 transit bridges

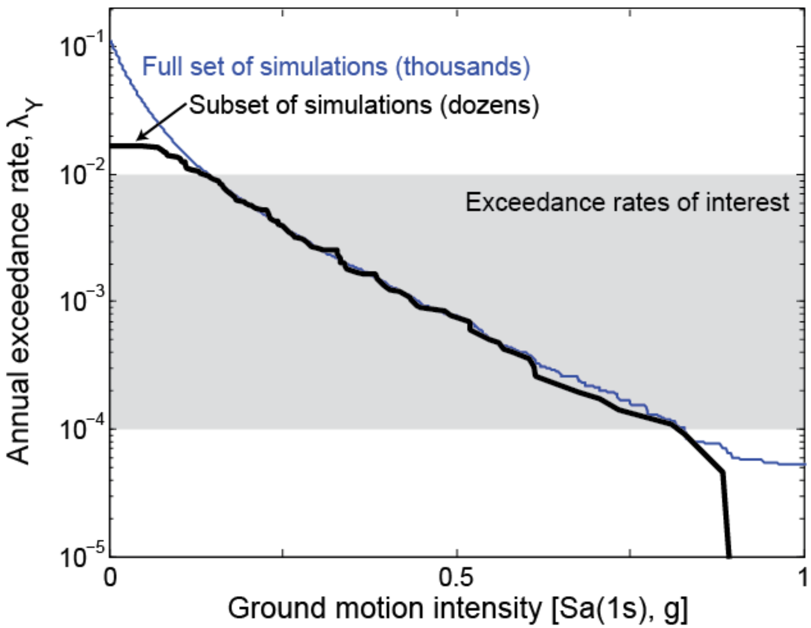
Here we consider major damage only (the bridge would be closed one week after an earthquake)

Adjacent bridges are likely to be simultaneously damaged due to spatial correlation in ground motions

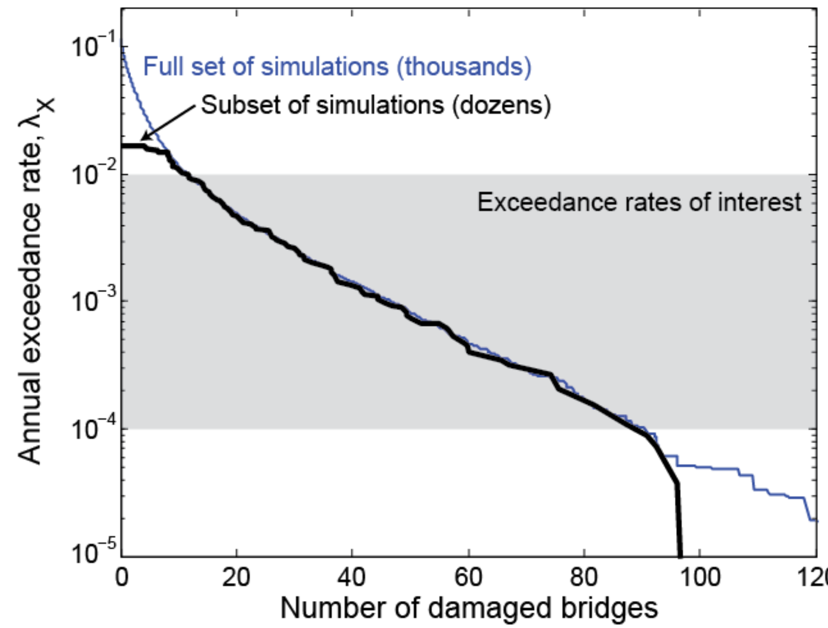


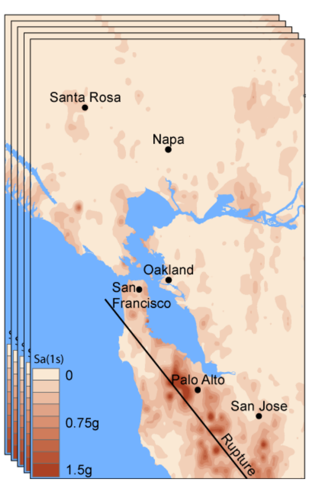
Reduce the number of simulations for network analysis

Ground motion hazard at a site



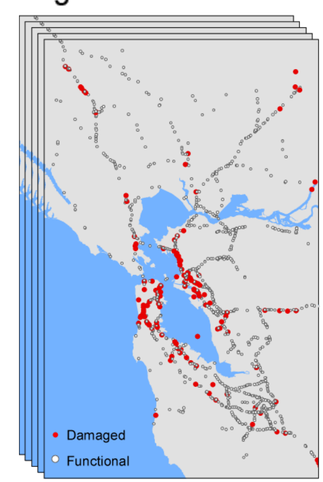
Proxy performance metric hazard





Select a subset of maps and reweight, to reproduce ground motion hazard at multiple sights and a proxy performance metric

Miller and Baker (2015). "Ground-motion intensity and damage map selection for probabilistic infrastructure network risk assessment using optimization." *EQ Engineering & Structural Dynamics*, 44(7), 1139–1156.

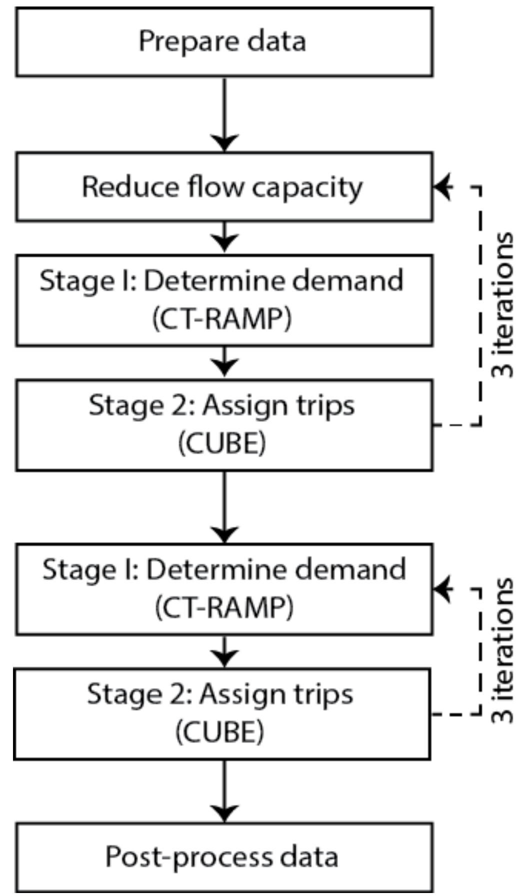


Step 3: Damaged network and network performance

We consider the network state one week after an earthquake

Transit model from the Metropolitan Transportation Commission

- Variable travel demand
- Population represented by agents with trip preferences
- 6+ hours to analyze network and behavior for one simulation



Miller, Cortes, Ory, Baker, (2015). "Estimating impacts of catastrophic network damage from earthquakes using an activity-based travel model." *Transportation Research Board 94th Annual Meeting*.

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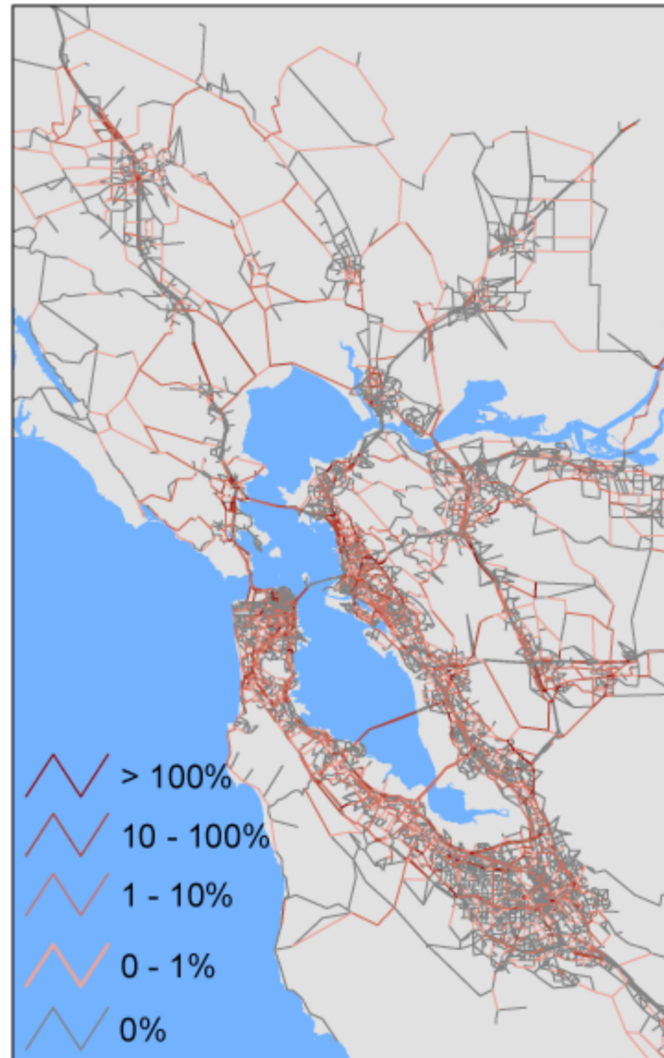
Travel time increase



Step 4: Measure user impacts

Each user has a set of transportation choices, made of

i = Mode (drive, bike, take a bus…)

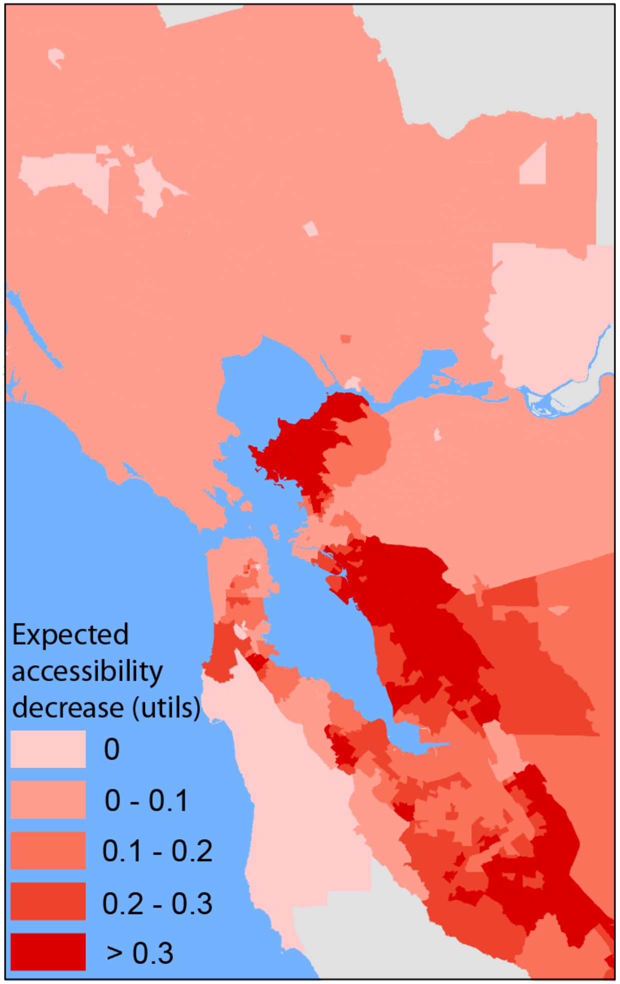
j = Destination (work, shopping, …)

U_{ij} = user *n*'s utility for mode *i* and destination *j* (calibrated from survey data)

Mode-Destination Accessibility measures these utilities (Niemeier 1997):

$$A_n = \ln \sum_{\text{all choices}} e^{U_{ij}}$$

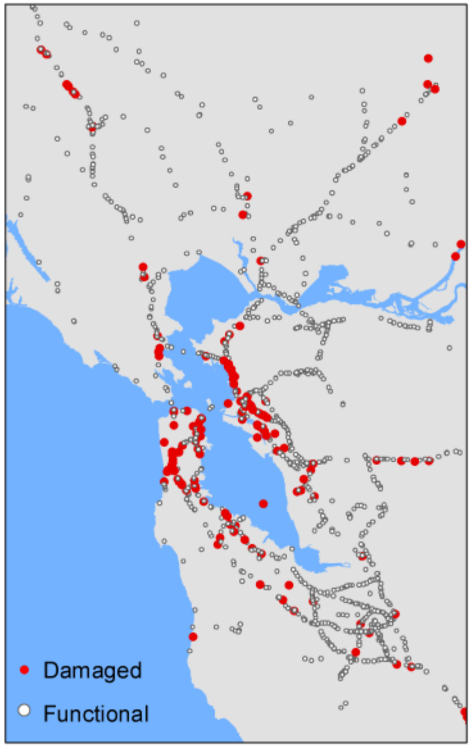
User accessibility decrease



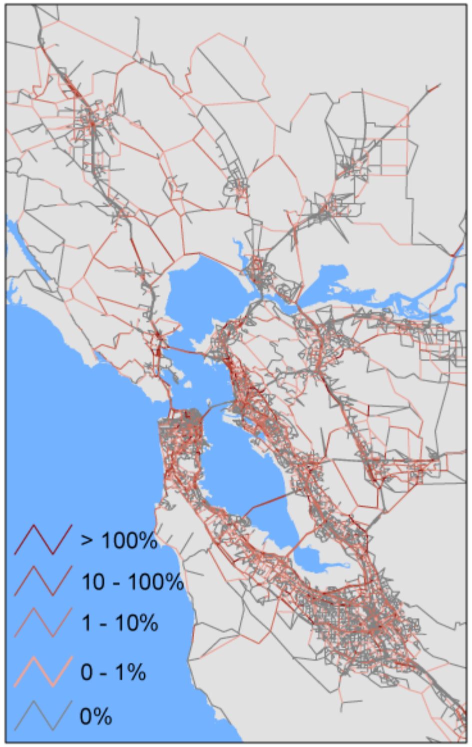
One simulation (of many possible events)

Earthquake ground motion

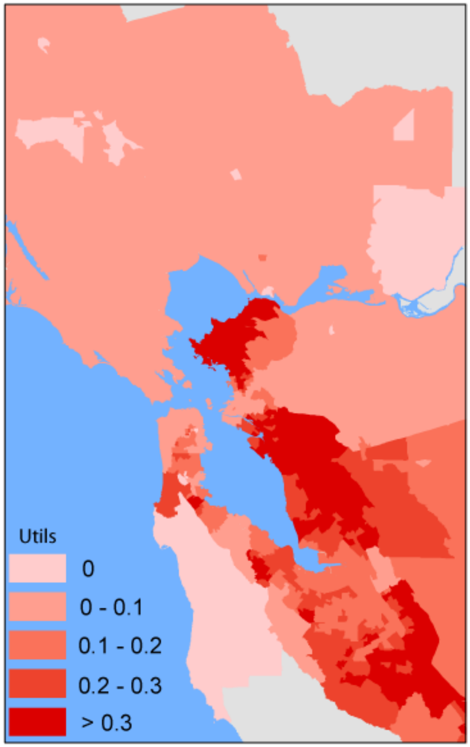
Bridge damage



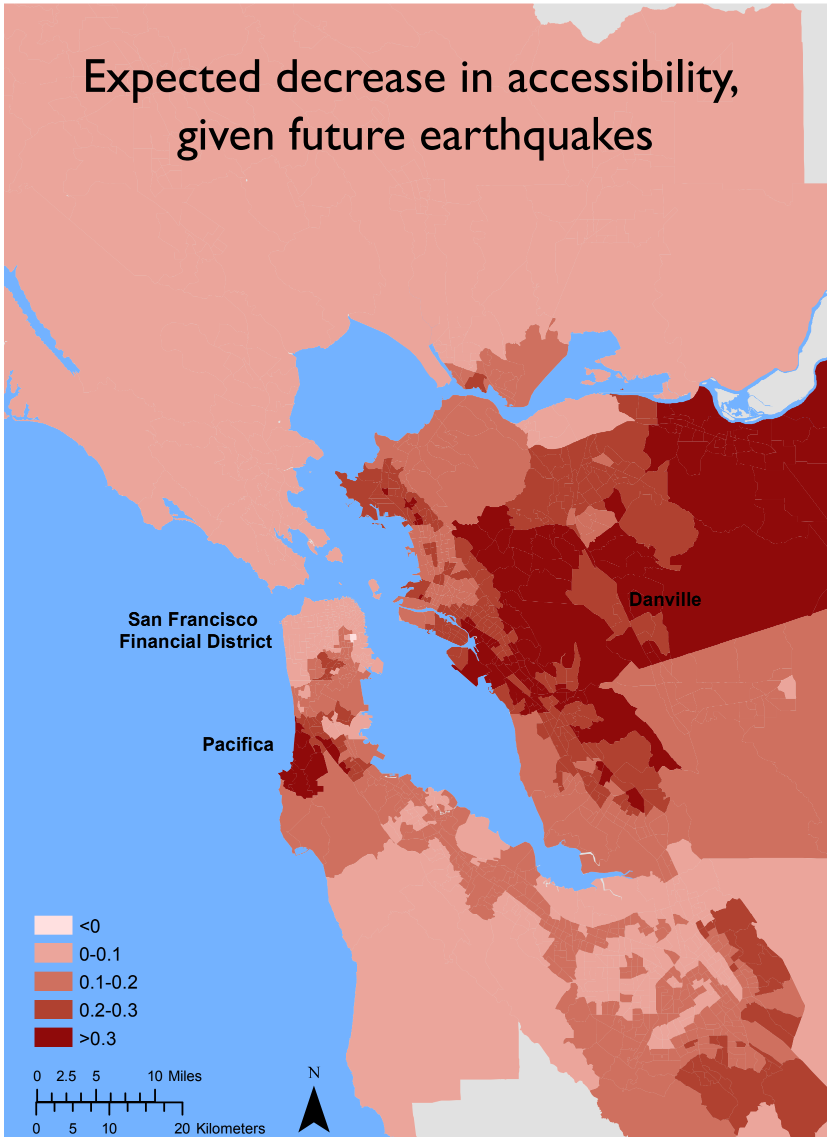
Travel time increase

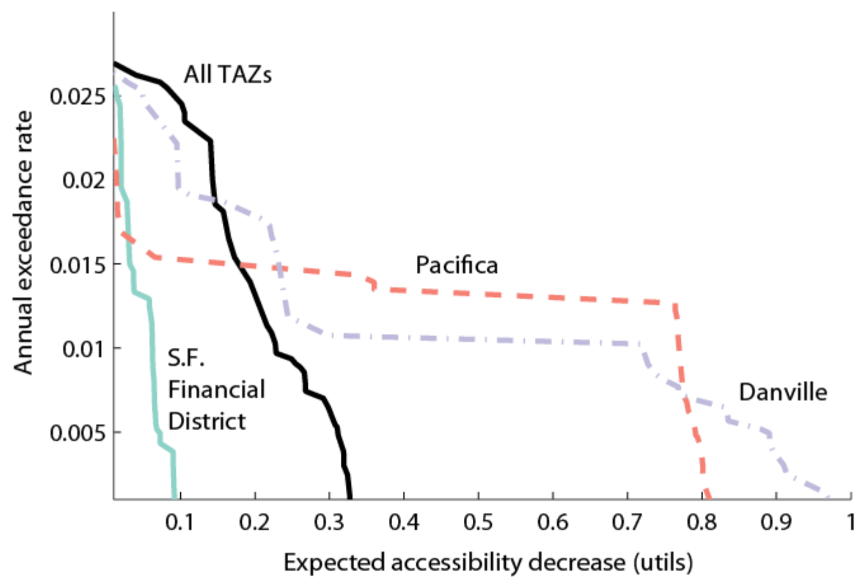


User accessibility decrease



Results: Three example communities





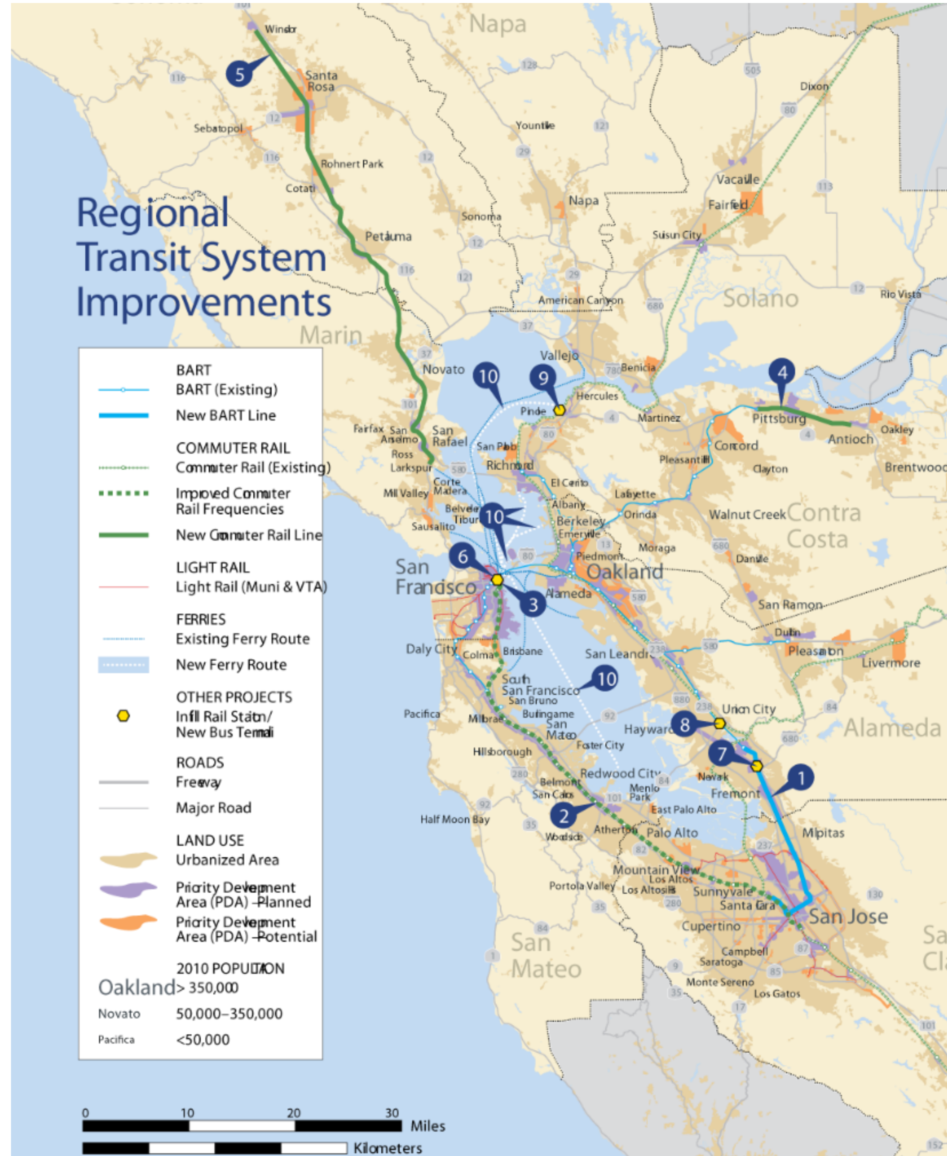
Miller, and Baker (2016). "Coupling mode-destination accessibility with a quantitative seismic-risk assessment to identify at-risk communities." *Reliability Engineering and System Safety*, 147, 60–71.

Decision support: Identifying retrofit priorities

Properties of critical network components (with respect to earthquakes):

- Vulnerable
- Located on highly trafficked routes
- Limited alternative routes

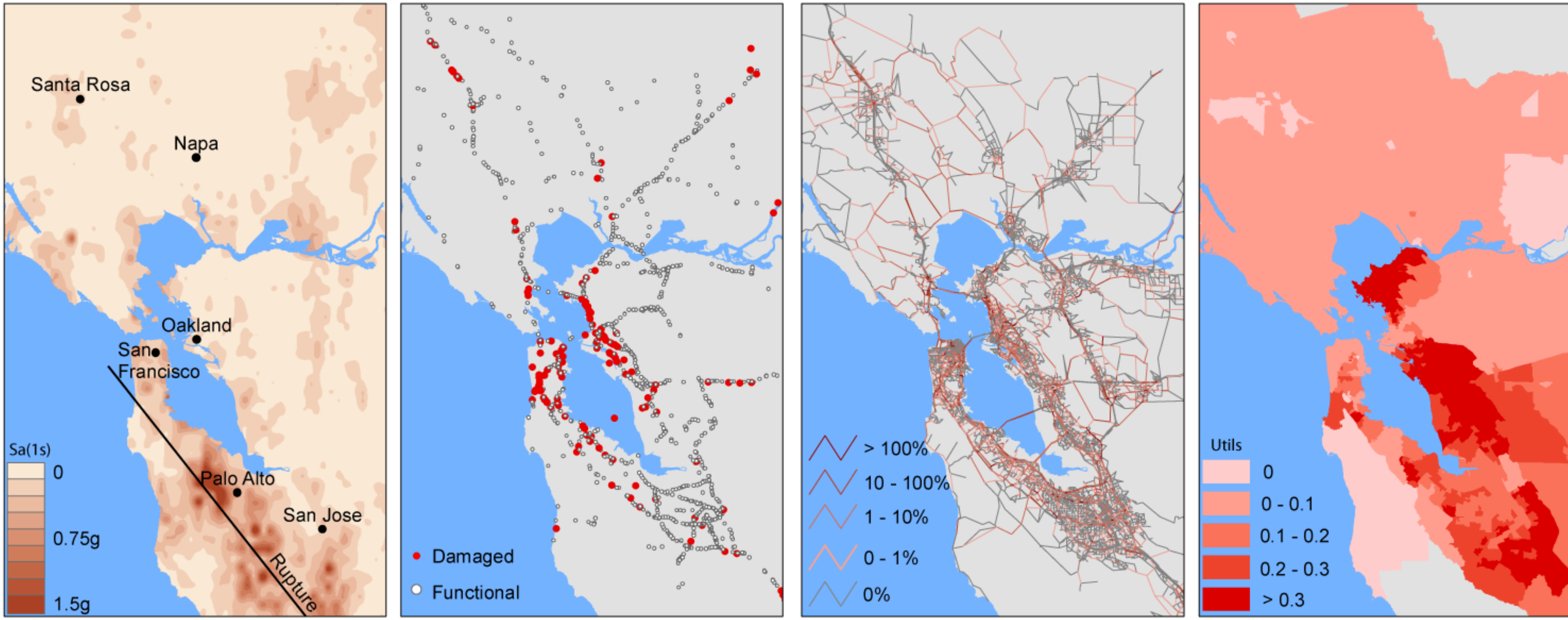
Can we more directly measure a component's importance to the network?



From Plan Bay Area (2013)

Our group's contributions in performance-based framework

Earthquake ground motion | Bridge damage | Travel time increase | User accessibility decrease



- Calibration of spatial correlations (and demonstration of impacts)
- Efficient simulation algorithms
- Optimization to select subsets

- Using transit models to model probabilistic earthquake risk
- Retrofit prioritization strategies

Conclusions

- The performance-based engineering paradigm transfers naturally to distributed infrastructure, with a few caveats
  – The "triple-integral" requires Monte Carlo simulation to evaluate
  – The "decision variable" can be complex to evaluate
- The benefits, in terms of decision support and producing metrics relevant to stakeholders, clearly still remain
- Our planned work:
  – Reduction of system risk by identifying optimal retrofits or upgrades
  – Simulation of the recovery process for resilience quantification

web.stanford.edu/~bakerjw