Local Measures of Disruption for Quantifying Seismic Risk and Reliability of Complex Networks

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ABSTRACT: This paper presents a study of seismic risk to a complex transportation system while quantifying disruption at the local level. The San Francisco Bay Area transportation system is considered as a case study. The network consists of 32,858 road segments, 3152 bridges subject to damage, and 43 transit modes. A refined model of this network's performance under damage, incorporating features such as transportation mode choice and dynamic demand, is used to predict disruption. Disruption is caused by earthquake shaking, where a full suite of earthquake scenarios in the region (with associated occurrence rates) are considered in order to obtain a fully probabilistic description of risk. Several strategies to manage the computational cost of this analysis are discussed. A number of network performance metrics are presented to provide insight into the disruption risks faced by residents of the region. Mode-destination accessibility, a metric based on network users' utility functions, is used here as a limit state to evaluate the potential disruption to individual users of the transportation system as it is a performance metric of interest to urban planners. Additionally, local measures of disruption, such as changes in the number of trips in and out of individual locales, are used to identify regions where users may be at particularly high risk of disruption. Using this complex network model, computationally efficient analysis strategies, and refined measures of disruption, we obtain new insights about users' risk, and obtain results in formats that are usable by urban planners responsible for long-term management of the transportation system's risk.

1. INTRODUCTION

Assessing risk to distributed infrastructure is important for societal decision-making, but quantifying reliability of complex networks subjected to natural disasters remains a challenging academic problem. To deal with challenges of limited information or limited computational resources, many infrastructure risk assessments are based on simplified network models. or, if they use a refined network model, on a single damage scenario.

Additionally, many network risk assessments are limited to considering network-level metrics of system performance, such as connectivity (Basöz and Kiremidjian 1995), weighted-shortest path between locations of interest (Chang and Nojima 2001), or total travel time for all users under fixed travel demand (Jayaram and Baker 2010). While some combinations of probabilistic network disruption and efficient system performance exist (e.g., Duenas-Osorio et al. 2007; Song and Ok 2010; Lim and Song 2012), these are in many cases limited to topological measures of network performance.

This study performs a probabilistic risk assessment of a complex transportation network, in order to understand risk associated with system damage. Seismic risk is quantified using a Monte Carlo “event based” framework, where the full range of earthquake events is quantified by efficiently sampling from the distribution of earthquake sources and resulting ground motions. We utilize a state-of-the-art activity-based travel model to model impact to users of damage to the network. Because the model has high local fidelity, we can look not only at system-level metrics of disruption, but also local measures.

This paper presents an overview of the models used to characterize seismic hazard and performance of the transportation network. The Bay Area transportation network is used as an example, and local performance metrics are used to demonstrate the potential insights of using these analysis approaches.

2. ACTIVITY-BASED TRANSPORATION MODEL

For this study, we utilize a refined multi-modal transportation model at the cutting edge of what is used by transportation planning professionals. We adapt the agent-based Travel Model One (Version 0.3), used by the Metropolitan Transportation Commission (MTC), the regional metropolitan planning organization (MPO) for the nine county San Francisco Bay Area. The road network in the study contains 32,858 road segments and connectors, 11,921 intersections and 1743 bridges subject to damage. Additionally, 43 transit systems (including bus, ferry and rail) are included, and 1409 additional bridges associated with those systems are subject to damage in earthquake shaking. When bridges are damaged, capacity of the associated segments is affected, and users may need to re-route.

The activity-based formulation of the model means that individual agents are free to take a different route, use a different transportation mode, or forego a trip entirely if it would take too much time. Each choice is associated with a utility for the agent, and each agent will make choices to maximize his or her utility. In this implementation of the model, agents representing 1% of the population are generated (i.e., each agent represents 100 actual people in the region with similar travel preferences). This choice provides accurate resolution while reducing computational expense relative to the case where a single agent represents each individual (Miller

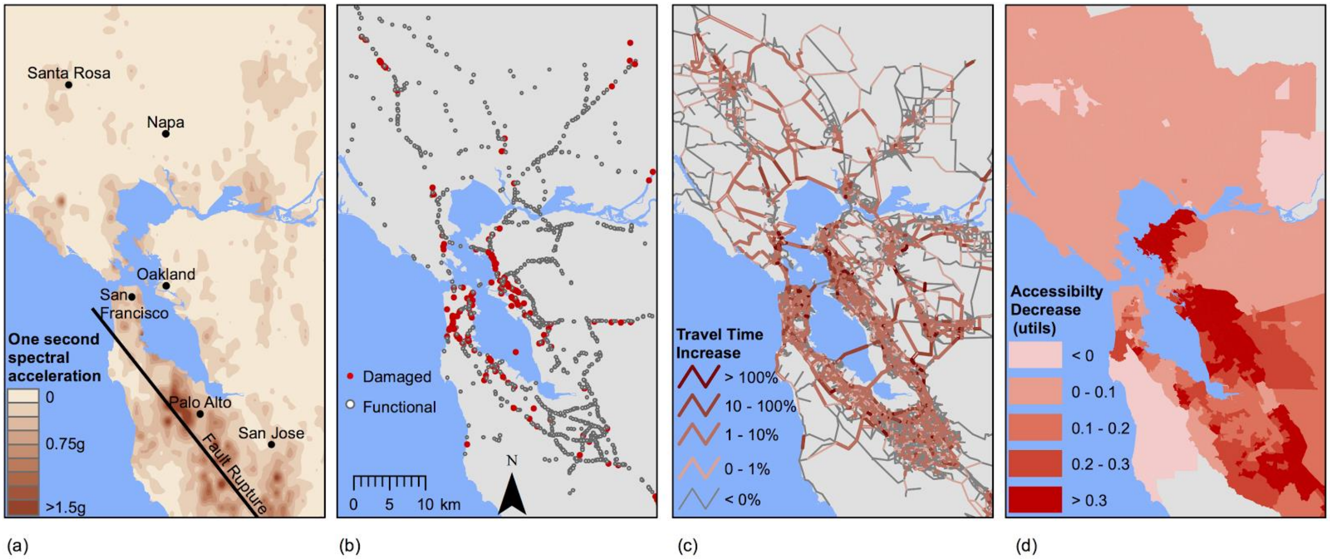

Figure 1: Schematic illustration of the event based simulation approach for quantifying seismic risk. (a) Earthquake scenario and ground motion, (b) component damage, (c) network performance, and (d) accessibility impacts (adapted from Miller 2014).

et al. 2015). This activity-based formulation makes the demand on the network dynamic, depending upon the level of disruption.

Travel on the network can be spatially aggregated in a number of ways. The region can be divided into nine counties, 34 superdistricts, or 1454 travel analysis zones (TAZs), depending upon the spatial resolution of interest. Miller (2014) provides additional detail regarding the transportation model, and how network activity is calculated in the case of a disrupted network.

3. RISK ASSESSMENT

Risk to the transportation network is modeled using a simulation-based approach illustrated schematically in Figure 2. The approach consists of generating a stochastic sample of potential ground motion intensities for the region of interest, simulating the resulting damage to bridges in the region due to the ground shaking, computing the functionality of the transportation network after bridge damage, and performing an activity-based simulation of transportation activity on the damaged network in order to understand region-wide as well as local impacts to the system. The simulation process is repeated a number of times for multiple events, in a Monte Carlo procedure similar to that used widely in the insurance industry to compute risk to portfolios of insured properties (e.g., Grossi et al. 2005). The following sections provide a summary of each step in this process, as implemented in the present study. Additional details are available in Miller (2014).

3.1. Ground motion simulation

The full Uniform California Earthquake Rupture Forecast (version 2) is considered (Field et al. 2009), via a suite of 2110 earthquake scenarios.

The OpenSHA event-set simulator is used to generate maps of median and standard deviations of resulting *Sa*(1s) intensities at each location of interest, using the Boore and Atkinson (2008) predictive model (Field et al. 2003). Spatially correlated residuals around these median predictions are then generated using the predictive model of Jayaram and Baker (2009a).

The ground motion intensity parameter of interest is *Sa*(1s): pseudo-spectral-acceleration at a period of 1 second and with 5% of critical damping. This measure was used for compatibility with the damage predictions described in the next section. Generating five realizations of ground motions for each of the 2110 potential earthquake scenarios resulted in 10,550 realizations of ground motions.

3.2. Component damage

The transportation network model contained 3152 bridges subject to damage—primarily state-owned bridges on the highway road network and elevated structures associated with the BART regional mass transit system. Additional bridges were identified and classified that affected other portions of the region’s transit systems, as described in more detail in Miller (2014)

Each bridge in the network is classified into a HAZUS category based on date of construction, number of spans, and other bridge features (NIBS 1999). This allows a fragility function to be obtained which predicts the probability of damage to the bridge as a function of *Sa*(1s). The HAZUS damage state of “extensive” is the limit state of interest here.

3.3. Network performance

Given component damage, we update the network’s properties accordingly. If damage is extensive or worse, the bridge is considered closed one week after the earthquake (the timeline of interest here); if damage is less than extensive, the bridge is considered functional one week post-earthquake (Werner et al. 2006). Any roads or transit lines passing over or under a closed bridge are considered non-functional (i.e., having zero capacity). It is noteworthy that these potentially critical interdependencies often occur between modes of the transportation system (e.g., a road crossing over a rail line). Feedback from transit system operators was used to determine how non-functional elements would relate to the decision to operate systems at partial capacity or completely close the system while repairs were underway.

Once the network capacities are updated, the transportation model is rerun to quantify the impact on travelers. To do this, the activity-based model is run with gradually reduced road and transit capacities (to maintain numerical stability as the agents are forced to modify their travel choices), iterating a number of times until the appropriate roads and transit lines are reduced to zero capacity and the network users are in equilibrium regarding their travel choices. Details of this procedure are available in Miller et al. (2015), and related procedures have been previously proposed by others (Chang et al. 2000; Han and Davidson 2012; Jayaram and Baker 2009b)..

Simulating impacts to the transportation network for each of these simulations is computationally expensive, as each of the network analyses takes 6+ hours even on a high-performance computing platform. To address this challenge, the initial set of several thousand ground motion maps and associated network damage were reduced down to a set of 40. The goal of the optimization was to select a small number of maps from the original 10,550, and reweight their associated occurrence rates, so that the selected subsample was an equivalent representation of the distribution of potential future ground shaking in the region. The distribution of interest is the multivariate distribution of *Sa*(1s) intensities at the 3152 bridge locations in the region. Several options are available to measure consistency of a sample of maps with this high-dimensional target distribution (Han and Davidson 2012; Jayaram and Baker 2009b) The reduction was performed here using the optimization procedure of Miller and Baker (2015). The optimization considered consistency of the subset with regard to ground motion hazard curves at individual locations (i.e., marginal distributions of shaking at individual sites) and risk to the transportation network as measured using simple metrics (a proxy for the joint distribution of ground motion intensities across the region). This approach is a computationally tractable and relatively robust way to selectively sample a small enough number of maps to be feasible to analyze, while maintaining the benefits of a Monte-Carlo-type analysis procedure.

The activity-based network was then run only for the 40 selected ground motion maps and damage scenarios. This allowed the computations to be performed in a reasonable amount of time (a few weeks) while still providing a probabilistic representation of the distribution of ground shaking that could be experienced in the region.

3.4. Accessibility impact

We quantify impact on travelers using a measure termed accessibility. This measure is computed by taking the log value of the sum of the exponentials of the utilities of each destination over all of a traveler's possible destinations and travel modes, where the utility decreases if getting to that destination is more costly or time-intensive (Handy and Niemeier 1997). This metric captures the fact that some destinations and trips have higher value than others, and also quantifies the cost of trips that are foregone due to network congestion.

With this metric, each user of the system has an accessibility score representing the impact of network damage on that particular user. These accessibility scores can then be aggregated in various ways to quantify the impact on users in particular regions or demographic groups, as discussed in the following section.

4. LOCAL MEASURES OF DISRUPTION

The risk assessment procedure provides a large amount of data—travel time and accessibility impacts for each modeled user and for each of the 40 earthquake scenarios. In total, 35,000,000 data points were used for this analysis. To aggregate the accessibility data in an informative manner, we compute the expected accessibility for a particular group as follows:

$$E\left[Acc_g\right]=\frac{1}{n_g}\sum_{j=1}^{40}\sum_{\forall i\in g}w_j^{'}Acc_{i,j} \qquad (1)$$

where $E[Acc_g]$ is the expected accessibility for group g (where a group is a set of users in a particular demographic group or geographic region). $Acc_{i,j}$ is the accessibility for agent i in earthquake scenario j, w'_j is the rate of occurrence of earthquake scenario j and n_g is the number of agents in group g. The summations are over all earthquake scenarios and over all agents in the specified group. In addition to expected accessibility, we also compute expected number of trips, expected travel time, and other measures in a similar manner.

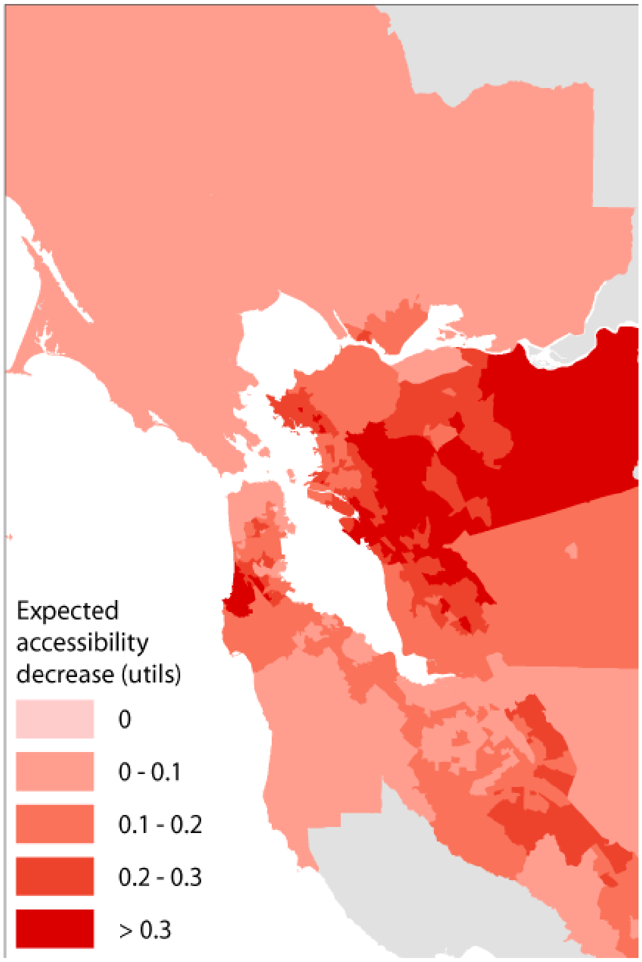

Figure 2: Expected decrease in utility per superdistrict in the study region.

To first provide a general sense of the risk for users in the network, Figure 2 shows the expected decrease in accessibility (relative to the expected accessibility for the undamaged network) grouped by TAZ. A "util" is a dimensionless quantity capturing the utility of the transportation system, equivalent to \$20 per person per day or 45 minutes per person per day. The expected utility decrease varies by approximately an order of magnitude across the region, indicating significant differences in risk for users living in different parts of the study area.

Figure 3 shows the average number of trips per day in the network with and without earthquake damage, and grouped by travel mode. There is a decrease in the number of transit trips, as the earthquake damage led transit systems to close in many earthquake scenarios. This is because some systems, such as the Caltrain light rail system, function as a weakest-link system and are completely inoperable if one relevant bridge suffers extensive damage.

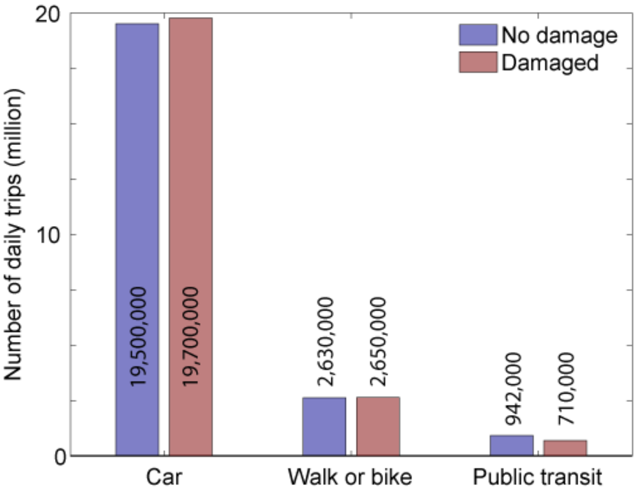

Figure 3: Average trips per day, grouped by travel mode, for the undamaged and damaged transportation network.

Next, aggregating agent behavior over geographic regions rather than travel modes, Figure 4 shows the percentage change in trips outside of a given county (relative to the trips in the undamaged network) grouped by agents in each of the nine counties in the region. Figure 3 showed that the region-wide number of trips does not change significantly due to earthquake damage (though some transfer from transit to car), but Figure 4 shows that inter-country trips decrease substantially, reflecting users' shifting from longer trips to more local trips when the network is damaged. Additionally, some counties experience a much greater reduction in out-of-county trips than others, indicating regional variation in the impacts of earthquake damage on travelers.

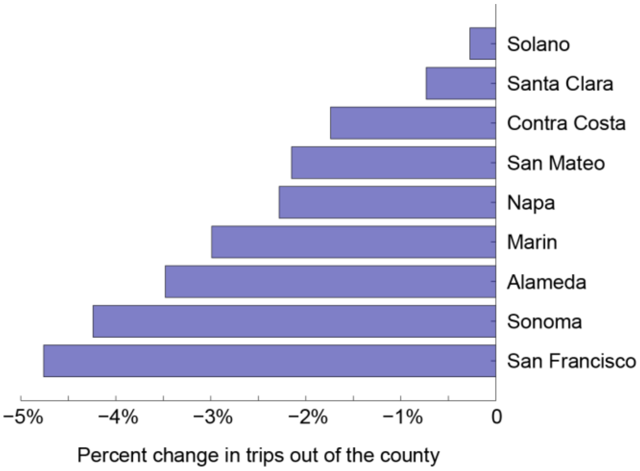

Figure 4: Percent change in number of trips outside of each county—expected number of trips in the damaged network relative to trips in the undamaged network.

Figure 5 shows the expected change in number of trips into San Francisco from other superdistricts in the region. It is notable that the superdistricts directly to the east of San Francisco suffer the greatest reductions in trips, reflecting both the large baseline number of trips from that region into San Francisco, as well as the anticipated difficulty of crossing the Bay if regional road and transit structures are damaged.

To get a sense of the number of baseline trips, as well as reduction in trips, Figure 6 plots both the initial number of trips out of each superdistrict (via the size of the circles in each superdistrict) as well as the expected reduction in trips given an earthquake (via the coloring of each district). This figure shows the reduction in trips out of each superdistrict to all other superdistricts unlike Figure 5, which considered only trips to San Francisco, so the geographic pattern of coloring differs somewhat. The largest reductions in trips still tend to group around the superdistricts close to the Bay, however, again reflecting the tendency for Bay crossings to get more difficult when the network is damaged.

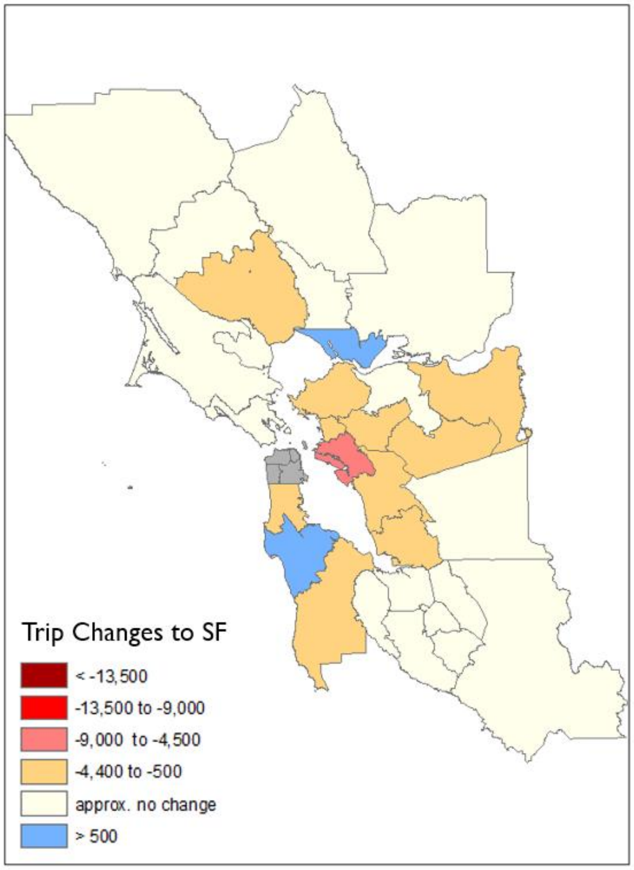

Figure 5: Expected change in the Number of Trips to San Francisco (SF) from each superdistrict.

5. CONCLUSIONS

This paper has coupled an activity-based transportation network model and a comprehensive model of seismic hazards to characterize potential damage to the network, and to quantify local measures of risk. For the case-study of the San Francisco Bay Area network, residents of the region east of San Francisco were noted as one example population group that may be at disproportionate risk of earthquake-related transportation disruption. A topic for future work is to study to what extent this disruption is due to risk of physical infrastructure damage, and to what extent it is due to congestion caused as an indirect consequence of having a network structure that suffers disproportionate impacts from minor damage. Such a quantification, if possible, would enable policy-makers to better target mitigation actions for risk reduction.

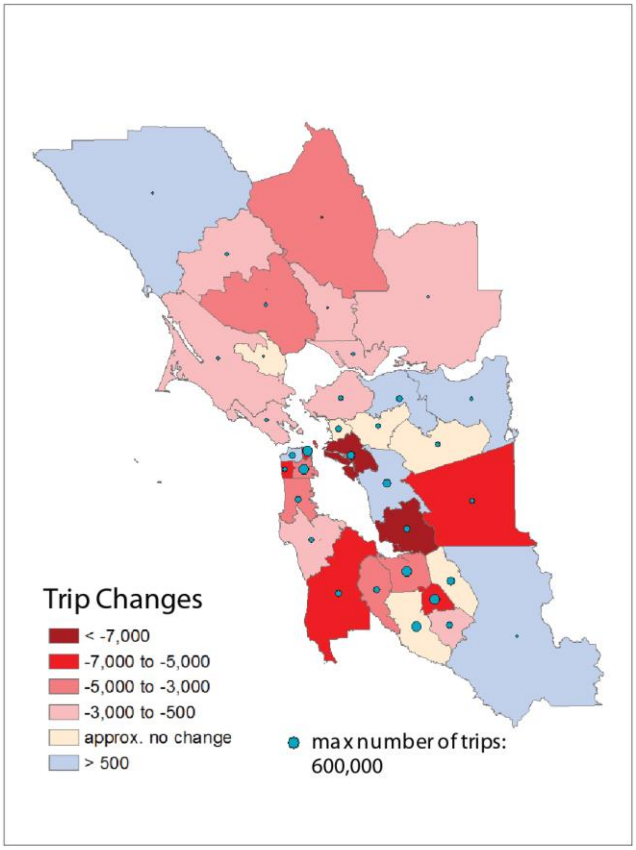

Figure 6: Expected change in number of trips out of each superdistrict. The size of circle in each superdistrict indicates the original number of trips out, and the colors indicate the mean change in number of trips out over the various earthquake scenarios.

By utilizing a full suite of probabilistic earthquake scenarios, the impacts reported here are true risk metrics (in terms of appropriately representing the probabilities of adverse events) rather than metrics conditional on the choice of an arbitrary earthquake scenario. Additionally, because the impacts were modeled using a network modeling approach that is preferred in the transportation-planning community, the results are readily digestible by transportation planning agencies. For these reasons, this work shows the feasibility of using reliability approaches to quantify risk to complex networks and provides a credible basis for making decisions to upgrade the network to reduce earthquake risk.

6. ACKNOWLEDGEMENTS

We thank Dave Ory at the Metropolitan Transportation Commission (MTC) and Tom Shantz and Loren Turner at Caltrans for motivating discussions and providing the case study data. The second author thanks the support of the NSF and Stanford Graduate Research Fellowships. This work was supported in part by the National Science Foundation under NSF grant number CMMI 0952402. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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