Advanced Engineering Informatics 46 (2020) 101159

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

CRAFT: Comprehensive Resilience Assessment Framework for Transportation Systems in Urban Areas

Eyuphan Koc[a,*,1], Barbaros Cetiner[b,1], Adam Rose[c], Lucio Soibelman[a], Ertugrul Taciroglu[b], Dan Wei[c]

[a] Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, United States
[b] Department of Civil and Environmental Engineering, University of California Los Angeles, CA, United States
[c] Sol Price School of Public Policy, University of Southern California, Los Angeles, CA, United States

ARTICLE INFO

Keywords:
Transportation systems
Mobility
Resilience
Image-based modeling
Economics
Urban policy

ABSTRACT

Urban areas in the US and around the globe are facing increasingly complex resilience challenges. Among the components of the "urban system," transportation networks are among the most critical facilitators that support the lives, interactions, and dynamics of urban dwellers. They are essential to the well-being of the society not only under business-as-usual conditions, but also during times of disaster for the entire response and recovery timeline. This paper introduces CRAFT (Comprehensive Resilience Assessment Framework for Transportation Systems in Urban Areas), which is designed to achieve holistic analyses of transportation disruptions by addressing the many shortcomings and research gaps in this domain. The framework couples a novel structure-specific modeling methodology with a high-fidelity metropolis-scale travel demand model based on real socioeconomic data, and produces results, which, in turn, serve as input for a state-of-the-art socioeconomic impact analysis methodology that is based on computable general equilibrium (CGE) analysis. By the virtues of its data-intensive, model-based, and cross-disciplinary nature, CRAFT aims to capture and incorporate many details that are usually neglected in traditional approaches, and generates resilience insights at 3 levels: (1) system component level (e.g., damages to bridges, tunnels and information on component recovery), (2) system level (e.g., road network disruptions, reconfiguration of traffic and network level functionality) and (3) regional economic level (e.g., impacts on regional GDP, employment, economic resilience). The objective of this paper is to introduce CRAFT and to demonstrate the workings of its first coupling between the hazard and transportation modules through a case study on the Greater Los Angeles Area.

1. Introduction

Disasters exert profound impacts on human societies. Direct costs of disasters have exceeded 2.5 trillion US dollars in the 21st century affecting more than 3 billion people and causing more than 1.2 million casualties around the globe[1]. Stemming from the inability to grow in a sustainable fashion, as well as to build resilience at the rate of urban growth, many cities are facing increasingly complex resilience challenges. This chronic trend is expected to continue as urban settlements grow in number and size. Approximately 70% of human population is projected to live in cities by 2050 [2]. This is foreshadowing even more exposure with higher concentrations of people, capital and infrastructure in urban areas. Recent events around the globe, including Hurricane Katrina and significant seismic events in Haiti, Chile, and Japan, have increased the awareness and the importance of resilience [3]. Consequently, the research area of 'urban (community) resilience' is attracting increasing interest over the last decade by many related disciplines.

The term urban resilience originates from ecological science which refers to "the ability of an *urban system*–and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales–to maintain or rapidly return to desired functions after a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity" [4]. Among the components of the urban system, infrastructure systems or *lifelines* are key facilitators that support the lives, interactions, and dynamics of urban dwellers. They are essential to the well-being of the society not only under business as usual conditions, but also during times of disaster for

* Corresponding author.
E-mail address: ekoc@usc.edu (E. Koc).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.aei.2020.101159
Received 10 December 2019; Received in revised form 9 July 2020; Accepted 18 August 2020
Available online 23 September 2020
1474-0346/

the entire response and recovery timeline. In this setting, it is argued that the transportation system is one of the most significant lifelines, because disturbance to transportation imposes extra burdens on other lifelines [5] (e.g. handling of a power substation failure due to earthquake damage requires a connected road network or other functioning modes of transportation for dispatch teams).

Transportation networks facilitate the mobility of people and goods, which is an immediate functional need in times of disaster serving search and rescue efforts, delivery of aid, etc. In addition to their role in emergency response, transportation systems are critical to the medium and long term economic recovery from a disaster which is often omitted in studies investigating the engineering aspects of (transportation) system resilience. For example, a detailed survey of business closures after the Northridge Earthquake in 1994 shows that 56.4% of the businesses reported *Employees Unable to Get to Work* and 24.0% reported *Could Not Deliver Products or Services* as reasons for closure [6]. Thus, the extent of transportation damage and the speed of its restoration are critical determinants of how quickly a disaster-stricken urban area can recover [7].

Transportation systems in the United States are aged and need a major retrofit or replacement effort. The American Society of Civil Engineers continuously gives the road and bridge inventories poor grades in its periodic infrastructure report card [8]. Transportation systems in large metropolitan areas that are exposed to natural hazards and possess characteristic vulnerabilities (e.g., earthquake exposure in the Greater Los Angeles Area along with vulnerability of bridges, storm surge risks in cities of Southeast US with vulnerable infrastructure in low-lying urban areas, etc.) are especially at risk. In addition, transportation systems have been repetitively targeted by terrorism, and resilience to such attacks have become strategic policy objectives for many countries including the US [9]. Further, many metropolitan areas operate their transportation systems at or near capacity during peak hours which projects significant functionality losses in case of a disturbance, despite a relatively higher redundancy in transportation systems compared to other lifelines.

Given the setting above, transportation disruptions have an increased interest from academic research. Despite this, *analytical* tools and approaches advising policy making to improve resilience are scarce [10]. In this paper, the authors also contend that there is also a lack of *synthetic* approaches that handle the diversity of challenges associated with transportation disruptions. Most investigations practically exclude one or more dimensions of the problem that stem innately from exposure to hazards, vulnerability of the physical infrastructure, and the direct and indirect losses that result from the coupling of the first two. Having this in mind, the authors intend to achieve a balance between the two overlapping views–analytical and synthetic– with a framework that is designed generate holistic and actionable resilience insights related to transportation network disruptions in metropolitan areas. The framework is called CRAFT for *Comprehensive Resilience Assessment Framework for Transportation Systems* and consists of: (1) a hazard characterization and damage assessment module that simulates the governing event causing the disruption (e.g. seismic hazard, tsunami, extreme wind, etc.) and estimates the physical damages to network components leveraging a novel image-based modeling methodology, (2) a transportation analysis module (implemented with a high-resolution travel demand model) investigating the disruption and (3) a socioeconomic impact analysis module based on CGE (computable general equilibrium) analysis supplemented by a multi-sector income distribution matrix that calculates the business interruption losses and income distribution impacts, and quantifies economic resilience. Standing on these three modules, CRAFT assesses 3 levels of resilience to in a study region: (1) system component level (e.g. bridges, tunnels), (2) system level (e.g. multi-modal transportation system of a metropolitan area), (3) regional economic level.

The objective of this paper is to introduce the framework and demonstrate the workings of its first coupling between the hazard and transportation modules through a case study in Greater Los Angeles Area. The authors additionally touch on the economic impact analysis module shining light on their current and future work fully deploying CRAFT.

2. Background

Research investigating transportation systems in the context of disasters originates from concepts and tools of traditional risk analysis. Therefore, understanding system vulnerability—as the *consequence* component of the well-known "set of triplets" [11]— has long been the focus. To that end, there is a substantial amount of literature on network vulnerability. Vulnerability for transportation networks is the *susceptibility to incidents that can result in considerable reductions in network serviceability* [12]. Resilience—defined as *ability of the civil system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance)* [13]—offers a broader perspective that highlights how the anticipating ability of vulnerability analysis must interact with the monitoring (*knowing what to look for*), responding (*knowing what to do*) and learning (*knowing what has happened*) abilities [14] in order to contribute to a more resilient system [15].

With the perspective of *embracing the failure when it is inevitable* and by covering the disruption timeline holistically, resilience has recently advanced to become the overarching concept and the preferred way-of-thinking in the transportation domain as well as in neighboring fields such as urban sciences [4] as opposed to being only a component of vulnerability analysis in the early prescription by Berdica [12]. Categorization of disaster measures used for transportation systems in support of this view (See Fig. 1) argue that resilience builds on a diverse set of system strengths and weaknesses as measured by risk, vulnerability, reliability, robustness, and survivability (i.e., resistance) and adaptability, while also encapsulating the system's ability to adapt to post-disaster circumstances as in flexibility measures [16].

Multiple reviews on transportation disruptions [15,16,18] draw the conclusion that the literature on system resilience is much less extensive in comparison to the works on system vulnerability (or robustness). Still, reviews identify limited signs of adoption of the abundant vulnerability related work by practitioners, planners and decision makers. Due to its mentioned characteristics, the authors believe that the resilience perspective offers an opportunity in achieving actionable insights. This is a key motivation for the cross-disciplinary collaboration behind CRAFT.

2.1. Towards comprehensive resilience assessment

Studies on disruption of transportation systems are generally grouped into two main methodological categories: *topological (graph*

Fig. 1. Disaster measures used for transportation systems, their boundaries and interactions [16,17].

theory-based) and *system-based approaches* [15]. In terms of data requirements, topological approaches only require the network topology to be known and quantify the disruption related measure (robustness, vulnerability, resilience, etc.) —based on network efficiency metrics such as the sum of the distance of shortest paths between all node pairs in the network, size of the largest connected component, etc.— in the case of random or strategic removal of nodes or links. Despite their practicality, topological assessments sacrifice insights regarding network supply and demand, consequently leaving out a considerable portion of transportation system analysis carried out today [19]. Moreover, topological approaches are subject to critique on their realism as disruption causing events are often not linked to the physical infrastructure inventories through formal hazard analysis and damage assessment methodologies.

System-based approaches offer a more holistic approach to transportation systems analysis. They require a focus on the interaction of network supply and demand allowing formal and realistic treatments of disruption related phenomena such as reduced link capacities, increased congestion, and decreasing redundancy. This way, resulting losses in network efficiency (functionality) that manifest in the form of worsening traffic conditions are quantified. Despite the benefits, these approaches are data hungry and require calibrated demand and supply models as well as sophisticated and commonly proprietary simulation platforms operating on traffic assignment algorithms to simulate mobility. In addition, if formal damage assessment is to be carried out to determine the vulnerability of network components (e.g., bridges, tunnels, etc.), hazard simulation models and detailed infrastructure inventories are required. Further, multi-disciplinary teams are required to capture the multiple mentioned angles of the transportation disruption problem in a metropolitan area. Nevertheless, system-based approaches provide the opportunity to capture the realities of transportation disruptions while keeping desired granularity in analyses intact, and pave the way for collaborations across disciplines and stakeholders to translate the advances in resilience research in different disciplinary silos to actionable insights for decision makers.

2.2. System-based analyses of transportation disruptions

System-based vulnerability is often quantified with respect to the marginal travel time/cost induced on the users in the degraded network. Nicholson and Du [20], in one of the early works to demonstrate this understanding, present a mathematical modelling approach based on a user equilibrium model to identify the mobility related impacts of degradation. The consideration of variable demand based on capacity fluctuations and the use of travel costs and system surplus as performance measures are valuable 'system-based' details in their work. Murray-Tuite and Mahmassani [21], in their two-player game theoretic approach (non-zero sum game between an evil entity and a traffic management agency) identifying critical components, define a vulnerability index accounting for the availability of alternate paths, excess capacity, and travel time. To set the stage for the network robustness index they define, Scott et al. [22] criticize conventional infrastructure management practices based on local Level-of-Service (LOS) measures (e.g., Volume/Capacity ratio) calculated at the link level. The authors argue local measures are misleading in determining areas of improvement in the network and illustrate the problem with a simple example. In Fig. 2, Link 2 is the more critical link based only on the V/C ratios, however, it is seen that Link 1 is more critical to the overall system since Link 2 cannot accommodate the rerouting of 3 units of volume in the case of a Link 1 closure. Based on this insight, Scott et al. [22]. define a Network Robustness Index (NRI) for evaluating the critical importance of a given highway segment (i.e., network link) to the *overall system*. Other researchers conducted work advancing and diversifying the research in this area in various ways such as allowing

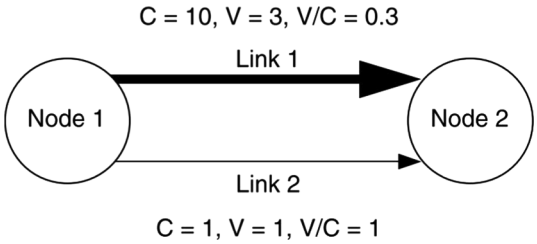


Fig. 2. Example illustrating critical links using V/C ratios [22].

partial link closures as opposed to binary treatment of failures Sullivan et al. [23], designing importance measures that are feasible in the case of non-connected networks [24] or focusing on changes in accessibility to investigate vulnerability[25,26].

Approaches mentioned so far on identifying critical nodes or links are applicable to disruptions resulting from the hypothetical degradation of a single or a pre-defined number of components in a network. In reality, natural hazards (e.g., earthquakes, floods, etc.) have spatially distributed impacts and different combinations of damaged components (i.e., closures) create different *disrupted* mobility patterns. Furthermore, computing the reduced accessibility–based on traffic assignment–for every node and link removal may be feasible for sparse regional/national level networks, however, this is not the case for dense metropolitan areas modeled with high resolution networks [27].

Some researchers followed yet another direction of research focusing on evaluating the vulnerability for specific regions and hazards [28]. Studies on economic impact analysis of transportation disruptions are also considered in this vein as a common objective in such studies is to quantify economic losses due to a specific (actual or hypothetical) event in a specific region [29].

To set the stage for the multi-disciplinary framework presented in this paper, research gaps identified by the authors are presented with respect to 3 perspectives: (1) (seismic) hazard characterization and damage assessment, (2) transportation systems analysis, (3) economic impact analysis. Table 1 summarizes these gaps.

Table 1
Shortcomings in system-based analyses of transportation disruptions: 3 perspectives.

I. *Hazard Characterization and Damage Assessment*
• Omission of formal hazard considerations, common tendency to look at failures without causes • Omission of structure-specific details as fragility analyses predominantly use archetypes • Misrepresentation of site-specific details such as shear-wave velocity, liquefaction susceptibility due to lack of in-situ measurements
II. *Transportation System Analysis*
• Lack of holistic and granular network modeling representing actual transportation infrastructure • Abundance of work in single link failures and/or a single mode of transportation. Limited for spatially distributed impacts and multiple modes • Post-disaster travel behavior treated as a mystery • Lack of attention to transportation equity related consequences and environmental impacts
III. *Socioeconomic Impact Analysis*
• Focus on individual component failures instead of a system-level analysis • Commonly used Input–Output models have well known limitations: they are linear, have rigid response and lack behavioral content • Rarely use explicit network modeling and formal hazard consideration

2.3. Shortcomings in system-based analyses of transportation disruptions: 3 perspectives

2.3.1. Perspective on hazard characterization and damage assessment

Prior to the discussions on shortcomings of hazard analyses carried out to inform analyses of transportation disruptions of this subsection, it is critical to highlight that formal considerations of the hazard itself and detailed inventories of the infrastructure systems are rarely included in past studies. This is in some measure due to the research objectives. If identification of critical links and nodes is the sole objective independent of the hazard [22,25], then formal hazard considerations are practically omitted. However, if the objective is to evaluate a network's performance against earthquakes, floods, etc., formal hazard characterization and damage assessment procedures need to be incorporated. The shortcoming here is that researchers traditionally resort to what-if assumptions to determine physical damages and component failures. Khademi et al. [18] finds in their review that many studies look at failures without their causes and focus on the failure of a single, hypothetical link (often links that carry the most traffic). This treatment of network degradation is not founded on component abilities to meet demands from hazards, thus they are generally limited in terms of generating realistic and actionable insights [27][2]. In this section, the shortcomings from this perspective are discussed to shine light on the contributions of the model-based methodology employed by CRAFT.

It is important to note that, here, for brevity, the discussion is formed on seismic considerations. Although the specifics for each hazard type might be different—e.g., seismic hazard at a site is defined based on the location, geological characteristics, and recurrence rates of seismic faults capable of affecting the site, whereas the storm surge hazard at a site due hurricanes is defined based on historical, hypothetical, or predicted hurricanes—the types of shortcomings are similar, if not identical. Hence, the weaknesses identified for the characterization of seismic hazard can be considered representative of the challenges in engineering representations of other natural hazards, including hurricane, flood, fire, and tsunami hazards.

In terms of damage assessment, significant shortcomings exist in engineering representations of the infrastructure serving the transportation networks [19]. The typical assumption made for the bridge and tunnel fragility functions is that they can be grouped into archetype structures [30,31]. This simplification may be warranted for tunnels. They constitute a diminutive portion of network components. Hence, in developing their fragility functions, there is a better chance of capturing the actual engineering properties by averaging. However, this is proved to be inapplicable to bridges. As reported by Jeon et al. [32] and Soleimani et al. [33], geometric properties such as the column height and shape, horizontal curvature, and abutment skew significantly impact the fragility functions of bridges. Nonetheless, widely used fragility functions, e.g., HAZUS relationships [34], do not consider any of these geometric features in formulating a relationship between IM and damage probabilities. As a result, studies based on such relationships are expected to result in inaccurate—most likely, as evidenced in Kircher et al. [35] for buildings, over-conservative—estimation of system performance. Accurate representation of site conditions is another area that requires improvements. The standard approach in defining site properties such as average shear-wave velocity for the upper 30-m, Vs30, liquefaction susceptibility for spatially distributed systems is to resort to proxy data sources (for instance, topographic or geologic information) without consideration to open access in-situ measurements. Such renditions may introduce notable degradation in the precision of ground-motion simulation or analysis results [36], hence reduce the overall quality of network performance evaluations.

2.3.2. Perspective on transportation systems analysis

In transportation systems analysis context, there is a lack of holistic and granular network modeling representing the multi-modal transportation infrastructure present in large metropolitan areas. This shortcoming is the result of an abstraction of the transportation networks when they could be modeled explicitly (e.g., modeling freeways only and neglecting arterial or surface streets, or various modes) [37]. Abstract network models do not allow the incorporation of realistic and locally relevant damage assessments from hazard simulations into the analyses. Abstraction or simplification may be acceptable for sparse regional or national networks (e.g., US Interstate System), however, dense networks in metropolitan areas need to modeled in a holistic manner not to blind assessments to the inherent redundancy—a key enabler of resilience—of transportation systems. Such limitations cause not only an underestimation of the role of networked transportation infrastructure, but also the omission of mobility constraints resulting from damaged infrastructure. Further, most of the studies focus on single link failures and/or a single mode of transportation[19]. Nagae et al. [38] points out suggestions by Asakura [39] on network models to be utilized in vulnerability research. According to Asakura [39], a network model developed for an ordinary network state should be modified and applied to the recovery state of a network, and the network flow model should have the characteristics of explicit link capacity constraints, decreasing demand due to traffic congestion and the uncertainty of a traveler's choice behavior. As discussed, such models have been rarely used in the area—even rarer at the metropolitan scale—and most studies resort to fixed demand assumptions and simplistic networks.

Second, post disaster travel behavior is largely treated as a mystery due to a lack of open, reliable, and high-resolution mobility data for post disaster situations [19]. In the case of catastrophic earthquakes, waiting for the disaster to happen to collect mobility data is clearly not an option. However, research should not refrain from utilizing existing demand models to predict post disaster traveler behavior, e.g. [26] even if the predictions depend on simple evaluations of existing demand functions or sensitivity analyses linked to what-if type assumptions[3]. This may be especially feasible for developed countries where earthquakes do not change travel patterns profiles as drastically as developing countries that are less prepared [18].

Nicholson [40] categorizes efforts for reducing road network unreliability into 4 categories (reduction, readiness, response and recovery) to argue that most of the prior research had looked into reduction options that focus on pre-disaster infrastructure improvements to reduce risks, and promotes the need for research in organizational planning for hazard events and decision support tools for prioritizing post-disaster response and recovery efforts. In their review, Khademi et al. [18] also identify the isolation of the pre-disaster phase by many studies. Mattsson and Jenelius [15] acknowledge these statements and further emphasize the need to cover the disaster timeline holistically as well as the need for strengthening cross-disciplinary collaborations with responsible authorities, operators and other stakeholders for mutual learning and transferring of knowledge.

Lastly, there is a lack of attention towards equity issues emerging from transportation disruptions. Assessments usually focus on the travel cost related consequences and predominantly quantify network functionality indicators such as increasing travel times and distances. These are considered more significant concerns, however, worsening in terms of such indicators result in environmental impacts (e.g., surging emissions due to increased use of vehicles) that are less focused on. Equity can also be discussed in terms of reduced accessibility or financial losses. To summarize, angles beyond the immediate mobility disturbances are often looked over and require more research attention.

[2] Still, it is essential to realize that what-if analyses might be the only viable option for certain events, e.g., terrorist attacks.

[3] An example research question can be: What portion of commuters would have to stay home for the post-disaster network to function at its pre-disaster level of functionality?

2.3.3. Perspective on economic impact analysis

The authors—with other collaborators—conducted a literature review on the economic impact studies focusing on transportation disruptions and identified research gaps [41]. In terms of the economic modeling approaches used in the reviewed studies, most articles only present an estimation of the *direct* impacts by simple mathematics. These articles do not take inter-industry diffusion effects or inter-regional economic activities into consideration. Among the articles with formal economic impact estimation methodologies, IO modeling in general and Interoperability Input–Output modeling are widely used approaches. In addition, there are several examples of the state-of-the-art approach in this area, CGE (Computable General Equilibrium) and Spatial CGE models (SCGE). The approach is that of a multi-market simulation model based on simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints [42].

The results of the literature review additionally showed that, with respect to the hazard impact information that is incorporated into the studies, most of the articles are based on simple assumptions such as the shutting down of a port over a week due to a hypothetical hazard [41]. This type of approach does not utilize a sophisticated understanding of a hazard and formal damage assessment procedures. In other words, state-of-the-art in hazard simulations are not utilized in most studies. Moreover, only a small subset of the articles in the review inventory carry out retrospective economic analyses based on reviewed or reported hazard information, i.e. actual disasters that have occurred in the past with documented and reported impacts. Another shortcoming of the literature in this domain is the lack of explicit network modeling and analysis in the quantification of system functionality. This abstraction results in a wide gap between engineering and economic analyses of the same phenomena. Among the few articles that incorporate explicit network modeling, most focus on the calculation of the direct transportation related costs such as increased travel or warehouse costs. Few studies estimated the indirect economic losses based on the direct losses (i.e. decreased proportion of initial production or demand along supply chains), which were hypothetical or simply set according to historical records[4].

3. Advances in modeling enabling CRAFT

Recent advances related to structure-specific and site-specific details in component modeling for regional damage assessment, and increased availability and standardization of spatial (network) data as well as the development of metropolis-scale travel demand models for transportation systems analyses are paving the way for improvements in the investigation of transportation disruptions. Moreover, economic models that are significantly more advanced than traditional I-O based models present outstanding opportunities to improve upon its well-known limitations. Discussion on these advances builds on earlier work by the authors [19].

In terms of component modeling, significant improvements can be made to bridge fragility functions if the geometric and structural traits for individual structures are considered in detail [19]. In the case of bridges, advancements in automated model generation based on LIDAR data [44], photogrammetric reconstructions [45], computer vision-based methods capable of extracting bridge models from street-level photographs [46], and the statistical studies on the moments [47] (i.e., mean, variance, of bridge structural properties) make it possible to attain substantial enhancements in the bridge fragility functions. These automated procedures are shown to be capable of capturing the structural response of bridges within a negligible margin of error. Further, as illustrated by [36], the site conditions at bridge locations can be defined at greater detail by constraining the proxy-based estimations of site characteristics with the public domain geologic, geophysical, and geotechnical data. This way, numerous site measurements, which are otherwise disregarded in evaluating network damage, can be effectively incorporated into the analyses. Subsequently, the damage induced by the principal damage mechanisms, including ground shaking, liquefaction, and surface rupture, can be better estimated.

From a network analysis viewpoint, advances in Geographic Information Systems data and software (e.g., OpenStreetMaps), increasing accessibility of computing resources, and standardized data formats (e.g. the General Transit Feed Specification) enable holistic modeling and simulation of multi-modal transportation networks of many urban areas around the world [19]. The traditional trade-offs between granularity and scale of analyses are deemed outdated thanks to such advancements. Therefore, research in the area should advance towards utilizing real scale network models that can incorporate spatially distributed impacts of catastrophic events rendering realistic and actionable insights possible for metropolitan transportation planning. In terms of travel demand modeling, large scale models are developed and maintained for planning purposes in many metropolitan areas in the US and around the world. Current travel demand models are based on extensive socioeconomic data (from Census, community surveys, trip surveys, etc.) and are validated against traffic counts observed in the actual network. Such models are rarely utilized for resilience assessments. To open up these detailed models for use in the research of transportation disruptions, the authors believe that collaborations are imperative to bring governmental agencies (e.g., metropolitan planning organizations, State DOTs and other transportation agencies, etc.) and researchers together. For example, the regional travel demand model in CRAFT is adopted from the Southern California Association of Governments (SCAG).

In terms of economic impact analysis, CGE analysis used for regional economic modeling–particularly for policy-making and impact analysis–is promising to improve upon the shortcomings of the I-O analyses. Being a competing approach to I-O analysis, CGE analysis has the ability to model economically resilient actions such as input substitution, conservation of resources, importing critical inputs, making use of inventories, etc [48]. Its capabilities make CGE analysis a more promising alternative in policy planning and disaster impact analysis. CGE analyses have been applied to infrastructure systems. Literature in the area provides findings related to transportation systems [49,50], energy policy [51], water infrastructure [52] and so on.

4. CRAFT: Comprehensive Resilience Assessment for Transportation Systems in Metropolitan Areas

In the light of the discussions on the background of transportation disruptions, perspectives presented on the shortcomings of research in this area and leveraging the mentioned advancements, a comprehensive framework, CRAFT, is designed for the assessment of resilience in metropolis-scale transportation networks. A modular approach was pursued in which—coming back full circle on Goldberg [53]—modules analyze corresponding portions of the problem with rigor and precision while the convergence captures a holistic view of resilience at 3 levels (See Fig. 3). The framework couples a novel structure-specific modeling methodology with a metropolis-scale travel demand model, and uses results thereof to inform an advanced economic impact analysis methodology. By virtue of its data-intensive and model-based nature, the proposed approach is capable of capturing and incorporating many details that are usually neglected in traditional analyses, enabling an improved thoroughness in the estimation of resilience and

[4] One of the efforts worth mentioning to this end is by Cho et al. [43] who modified the original Southern California Planning Model (SCPM1) to develop an integrated, operational model that measures losses due to earthquake impacts on transportation and industrial capacity, and how these losses affect the metropolitan economy. This is one of the rare interdisciplinary efforts with an overarching approach despite the limitations of the economic and transportation models employed.

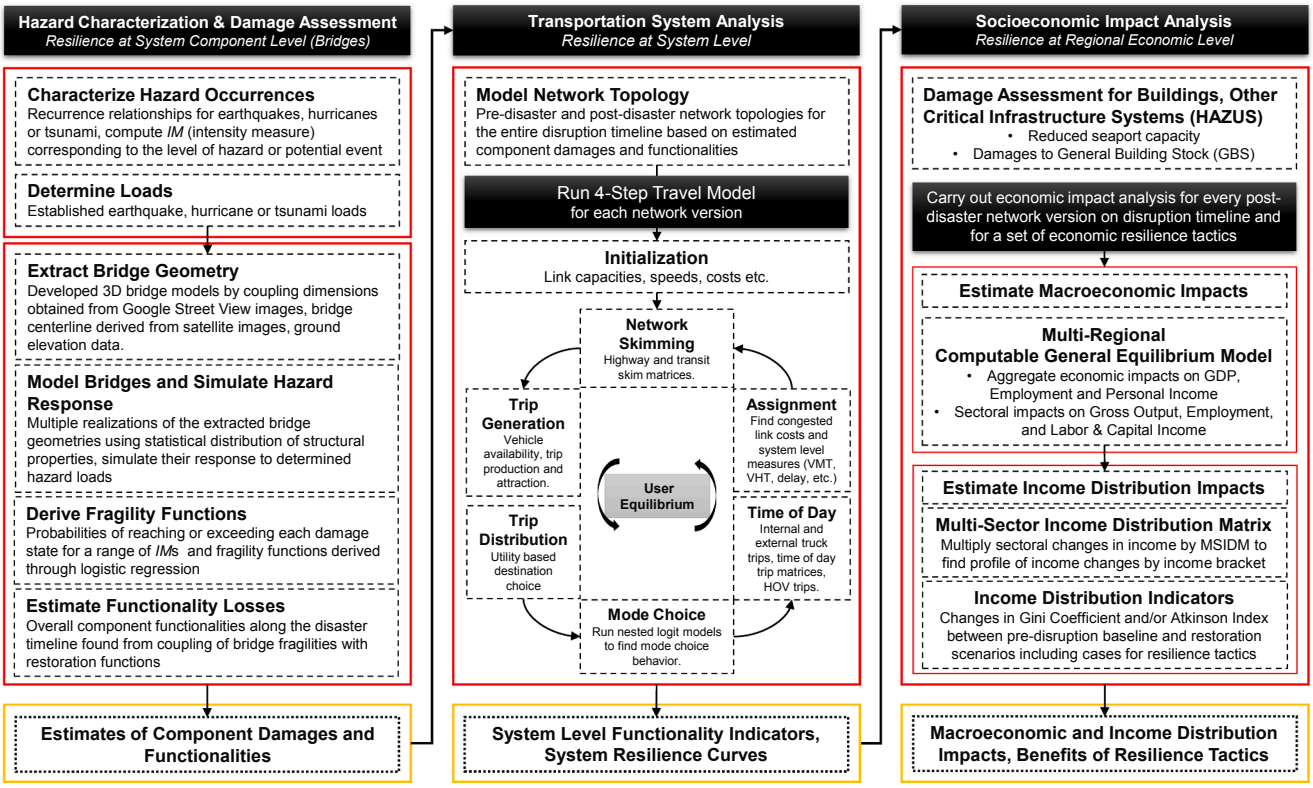


Fig. 3. A conceptual illustration of CRAFT: Comprehensive Resilience Assessment Framework for Transportation Systems. The reader is referred to the web version of this article to see all figures in color.

sustainability metrics of transportation networks. As the test-bed for the proposed framework, a study region aligning with the Southern California Association of Governments (SCAG) area of responsibility including 6 counties in Southern California (Imperial, Los Angeles, Orange, Riverside, San Bernardino and Ventura) is used.

4.1. Resilience at system component level: hazard characterization and damage assessment

CRAFT is not hazard-specific. The methodology behind CRAFT is, by design, capable of accommodating resilience assessment for various hazards in a coupled or decoupled manner. Given a comprehensive description of the steps required for representing each type of hazard cannot be realized within the space limitations of this work, in the following, only the seismic characterization approach used for the case study discussed in the next section is described.

Characterizing seismic hazards for a region require translating the knowledge of potential seismic sources into simulations of realistic and locally relevant deterministic hazard scenarios. The seismic demands resulting from these hazard scenarios are then used to predict damage to—and ultimately, the recovery of—network components.

The procedure for converting seismic hazards to direct inventory damage consists of three principal components: *(i)* quantifying deterministic seismic hazard governing an urban transportation network, *(ii)* coupling the intensity measures (IMs) resulting from the seismic hazard with component fragility functions to estimate the damage state probabilities, and *(iii)* combining the damage state probabilities with restoration functions to calculate the downtime for each network component. [37].

The first step in quantifying the deterministic seismic hazard is identifying the *scenario earthquake(s)* controlling the overall seismic hazard for the network—also known as probabilistic seismic hazard analysis (PSHA) [54]. The regular practice in determining the fault line, location, and magnitude associated with a scenario earthquake is "deaggregating" the probabilistic seismic hazard (PSH) results so that the relative contributions of all seismic sources to that hazard are displayed for all possible magnitude and distance measures [55]. Once the scenario earthquake is identified, it is possible to calculate the rupture length of the fault segment using the Wells-Coppersmith relationship

$$\log_{10} L = a + b \cdot M \tag{1}$$

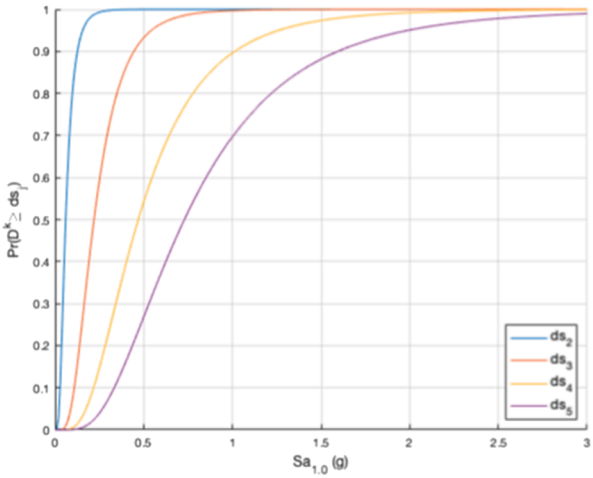
where L is the rupture length in km, M is the moment magnitude of the earthquake, and a and b are the regression coefficients [56]. The final step in computing the deterministic hazard is to calculate the IMs resulting from the defined earthquake event. This is typically performed by passing the source information to ground motion prediction equations (GMPEs), such as the ones developed through the NGA-West 2, and NGA East projects [57,58]. In a GMPE, the natural logarithm of a ground motion IM ($\ln Y$) is coupled with a source function (F_E), path function, (F_P), site function (F_S), and a residual term $\varepsilon_n \sigma(.)$ through the relationship

$$\ln Y = F_E(\mathbf{M}, mech) + F_P(R, \mathbf{M}, region) + F_S(V_{S30}, R, \mathbf{M}, region, z_1) + \varepsilon_n \sigma(\mathbf{M}, R, V_{S30}) \tag{2}$$

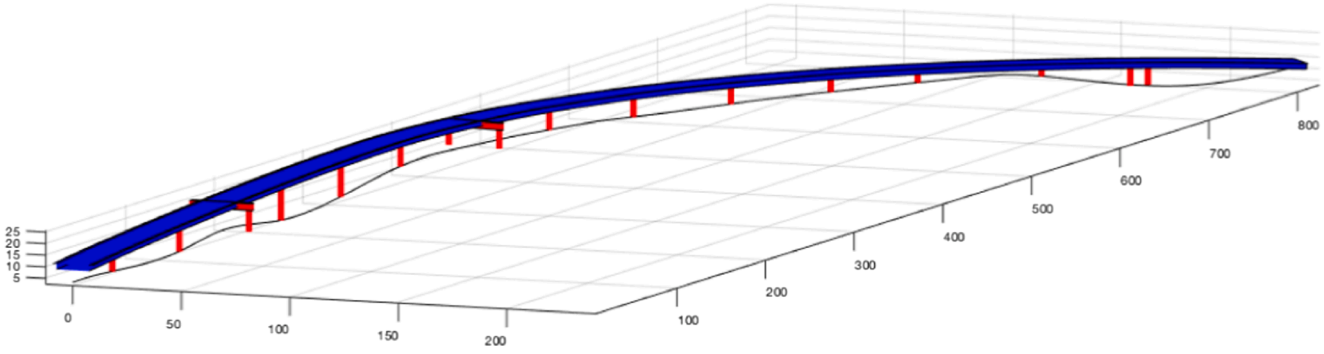
where $\mathbf{M}$ is the earthquake moment magnitude, R is the closest distance to the rupture plane in km, V_{S30} is the time-averaged shear-wave velocity in the top 30 m of the site in m/s, z_1 is the basin depth in km, *mech* is the fault mechanism parameter, and *region* is the regional correction parameter.

The main outputs of GMPEs are the IMs peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped elastic pseudo-absolute spectral acceleration (SA). Combining PGA with information such as liquefaction susceptibility, the IM peak ground displacement (PGD) at a site can also be calculated. Each of these IMs correlate with a particular type of seismic demand and the corresponding damage to individual network components. During an earthquake, the primary factors that contribute to bridge losses are ground and structural

(a) Google Street View images



(b) Bridge fragility functions



(c) 3-D geometric model

Fig. 4. Several Google Street View images (a), fragility functions (b), and geometric model (c) obtained for a bridge considered in this study.

failures, which are typically well-correlated with PGA [59] and SA [60], respectively. Damages to tunnels, on the other hand, are caused by ground shaking, ground failure due to liquefaction, fault displacement, or slope instabilities. As such, tunnel seismic damage levels are well correlated to (and thus can be described as a function of) PGA and PGD [61].

The relationship between network components and IMs are defined using fragility functions. Fragility functions are log normally-distributed functions that give the probability of reaching or exceeding different damage states for a given IM. In performance-based earthquake engineering (PBEE) practice, damage to a network component is categorized into five damage states, namely no damage (ds_1), and slight (ds_2), moderate (ds_3), extensive (ds_4), and complete (ds_5) damage states [62]. Each fragility function corresponds to one of these damage states and is characterized by a median value IM (M), and a log-normal standard deviation value (β). The generic form of a fragility function is given by

$$\Pr(D^k \geqslant \mathrm{ds}_j) = 1 - \Phi_j^k\left(\frac{\ln(x^k/M)}{\beta}\right) \tag{3}$$

where k is the index for IMs, j is the index for PBEE damage states, D^k is the damage state of network component due to IM k, Φ is the normal cumulative distribution function, and x^k is the IM k at the site of the network component. Note that the probability of a system being in or exceeding the no damage, ds_1, state is always 1 ($\Pr(D^k \geqslant \mathrm{ds}_1) = 1$).

An essential input for resilience assessment is the downtime estimates. Thus, for resilience studies, damage probabilities computed using fragility functions are converted into this metric. Translating bridge fragilities to downtime requires calculating the probability of network components being in one of the five damage states, and aggregating these probability measures to restoration functions that correspond to individual damage states. Open literature on restoration functions is particularly limited, and the restoration functions published by FEMA [63] are the main tool used for tying component damage information to downtime estimates. For a set of IMs, the probability of a network component being in a damage state (P_j^k) is calculated as

$$P_j^k = \begin{cases} \Pr(D^k \geqslant \mathrm{ds}_j) - \Pr(D^k \geqslant \mathrm{ds}_{j+1}) & j = 1, 2, 3, 4 \\ \Pr(D^k \geqslant \mathrm{ds}_5) & j = 5 \end{cases} \tag{4}$$

For a set of IMs, expected downtime ($E[D^k]$) is defined with respect to P_j^k as in

$$E[D^k] = \sum_{j=1}^{5} P_j^k \cdot RC_j \tag{5}$$

where RC_j is the recovery function corresponding to the damage state denoted by index j.

As outlined in NIBS [64,65], HAZUS-type fragility functions based on archetype classifications have a tendency to overestimate physical damages for earthquakes with M<6 and underestimate the damages for events with M⩾ 6. In other words, traditional fragility functions offer

limited accuracy in predicting component-level disruptions. One of the novel contributions of CRAFT is its use of detailed bridge fragility functions generated using the image-based modeling approach proposed by Cetiner [46]. The method establishes structural models of bridges via a fusion of geotagged street-level and satellite imagery, OpenStreetMaps centerline curves [66], 2018 version of National Bridge Inventory (NBI) metadata [67], Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data [68], and class statistics for bridge structural properties available in the literature [47]. The central premise of the method is that through auto-calibration from multiple uncalibrated street-level images, the camera matrix can be determined. Also, by semantic segmentation, individual components of a bridge can be identified in images. Subsequently, by measuring the distance between the back-projection of image origin and the image locations of components, world coordinates of the components can be computed and superimposed on the bridge centerline. Furthermore, object dimensions and deck height can be extracted, and a geometric model of the bridge can be computed. The geometric model can then be laid over the SRTM digital elevation model and populated with class statics to attain a comprehensive structural model of the bridge. Here, the described process is implemented using an in-house code developed specifically for this purpose. For further details of this implementation, the reader is referred to Cetiner [46]. Fig. 4(a) shows a snapshot of Google StreetView images selected for one of the bridges modeled for this study. Fig. 4(c) displays the 3D model generated for this bridge using the procedure summarize above.

The process of obtaining bridge-specific fragility functions for ground shaking involves performing incremental dynamic analysis (IDE) [69] of individual bridge models. By calculating the seismic response of a bridge for multiple ground motions at a range of $SA_{1.0}$ levels and comparing the demands determined for each realization against the corresponding damage thresholds for each damage, IDE computes the $\Pr(D^k \geqslant ds_j)$. The choice of ground motion records and the damage thresholds for each damage state depends on a variety of factors. In selecting ground motions, using a dataset, which consists of waveforms from earthquakes with magnitude and distance measures compatible with the scenario earthquake, that covers a broad band of frequencies is crucial. The key aspect of determining damage thresholds, on the other hand, is to ascertain that they are applicable to the structural systems that comprise the bridge. In this study the ground motion dataset suggested by Baker et al. [70] and the threshold values employed by Ramanathan et al. [71] are utilized. Fig. 4(b) shows the fragility functions obtained for the bridge model displayed in Fig. 4(c) for the damage states ds_2 to ds_5.

4.2. Resilience at system level: transportation system analysis

In the light of the presented perspective on shortcomings of system-based analysis of transportation disruptions, the novel image-based damage assessment methodology discussed in Section 4.1 is coupled with a transportation system analysis methodology to achieve resilience insights at the *system level* (See Fig. 3).

Based on the results of the damage assessment procedure in the previous section, the analysis of the transportation network disruption is realized with a metropolis scale 4-step travel demand model. Specifically, functionalities of damaged system components are evaluated with respect to a link closure policy with a threshold parameter. This is done to replace the decisions based on post-disaster manual inspections in a consistent manner. In the case of bridges, if a bridge is damaged beyond the threshold, the link corresponding to that bridge in the network model underlying the travel demand model is—partially or fully—closed to operation. The restoration functions embedded into the damage assessment provide the information on the duration of closures. With this information, a number of network topologies (pre-disaster baseline and post-disaster degraded versions) are modeled to capture the network supply conditions throughout the disruption timeline (*Initialization*). Initial skim matrices are computed to find the OD costs for TAZ (Traffic Analysis Zone) pairs (*Network Skimming*). These costs inform *Trip Generation* where trip production and trip attraction models estimate the number of trips generated for all trip purposes (from and to all TAZs) which are then balanced and distributed throughout the region via different modes (*Trip Distribution and Mode Choice*). The calculated travel demand is then segmented into finer time periods (*Time-of-Day Choice*) and are used to assign the loads into the network to solve for the traffic assignment problem (*Assignment*). With the new 'congested' link costs, a new iteration begins with *Network Skimming* and this loop runs until convergence to user-equilibrium. CRAFT implements this methodology, for every network topology (pre-disaster baseline and post-disaster degraded versions).

The methodology, however, may differ based on the modeling the travel demand after the initial disruption. Often in system-based analyses of transportation disruptions, researchers assume fixed demand conditions in which the same trip matrices are fed into traffic assignment for different topologies. This way, an understanding of overall system functionality is gathered in settings where various levels of lesser network supply attempts to serve the same travel demand. In this case, the analysis employs trip generation, trip distribution, mode choice and time-of-day choice models only for the pre-disaster baseline network. Another option is to run trip generation, trip distribution and mode choice models based on the degraded topologies and try to capture the interaction between varying travel demand and network supply. However, since data on post-disaster travel demand and calibrated models thereof are largely incomplete (relative to the data and models for pre-disaster baseline settings), such analyses fundamentally depend on existing models of travel demand that are commonly generated from and calibrated to data from a typical weekday in the study region.

Traffic assignment results for all network topologies allow for the assessment of network functionality until full recovery with respect to a business-as-usual (pre-disaster) baseline. This way, the system resilience curve can be drawn for the regional transportation system, shining light on 3 of the 4 resilience properties proposed by Bruneau et al. [13]: *robustness*, *redundancy* and *rapidity*. Investigating *resourcefulness* is traditionally more challenging due to the unknowns associated with the resources of transportation agencies and other stakeholders for response and recovery. However, CRAFT allows for sensitivity analyses focusing on optimal response and recovery interventions as tactics of enhancing resilience [72].

In the investigation of system resilience as an emergent capability for the transportation system, the following analytical resilience definition of Frangopol and Bocchini [73] is adopted here:

$$R = 1/h \int_t^{t+h} Q(t)dt \tag{6}$$

where t is the instant in which the disruption occurs and h is the investigated time horizon and $Q(t)$ is an indicator of system functionality. In this definition, resilience is quantified as the area under the functionality curve with respect to 100% functionality throughout the investigated time horizon. Integrating functionality over time in this manner gives network resilience, R, to the specific hazard scenario. Revising the definition by Frangopol and Bocchini [73], the authors define Q(t) relative to a baseline, $\Gamma_i(0)$, indicating system functionality with respect to indicator i on a typical day in pre-disaster settings, i.e. *day* 0. This is done to quantify the functionality of the disrupted versions of the system relative to a *business-as-usual* baseline. This way, the extreme case considered by Frangopol and Bocchini [73] where all the bridges are out-of-service is also left out as it is not a realistic one for metropolis-scale systems.

$$Q(t) = 1 - \frac{|\Gamma(t) - \Gamma(0)|}{\Gamma(0)}; \quad Q(t) \epsilon [0, 1] \subset R \tag{7}$$

A number of functionality indicators, Γ, are proposed in literature

that are commonly quantified based on the total travel time spent or total travel distance covered in the system by all users. Other indicators such as average speed or emission levels can be used. Being centered around a detailed, high-resolution model of the transportation system, CRAFT allows for the quantification of virtually all such indicators. $\Gamma_i(t)$ is typically calculated as a sum over all links in the network at time t for indicator i for indicators such as *VMT* (Vehicle-Miles-Traveled), *VHT* (Vehicle-Hours-Traveled), *Delay* (Vehicle-Hours-Delayed) (See Eq. (3)). Other less visited indicators such average speed can be calculated as a mean over all the links.

$$\Gamma_i(t) = \sum_{links} \text{FunctionalityIndicator}_i(t); \quad \Gamma_i(t) \in R^+ \tag{8}$$

4.2.1. SCAG regional travel model

The transportation system analysis component of CRAFT illustrated with the workflow in Fig. 3 is currently implemented with the regional travel demand model (RTDM) developed by the Southern California Association of Governments (SCAG), as part of their regional transportation plan [74]. The peer-reviewed model is developed and operated on TransCAD. The SCAG RTDM uses a number of datasets for modeling and validation purposes. For modeling, zonal data at the level of Traffic Analysis Zones (TAZs) including population and household characteristics (household size, annual income, education, employment etc.), travel survey, land use data are essential for estimating the travel demand in the region. Most of these data come from Public Use Microsample Data (PUMS), U.S. Census, California Department of Finance, Californiat Employment Development Department (EDD), Land Use and County Assessor's Parcel Database among other local data sources. Consequently, the model's travel demand estimation components utilize 65 socio-economic variables and 8 joint distributions of two or more variables. For calibration and validation, California Household Travel Survey, Vehicle Miles of Travel (VMT) from Highway Performance Monitoring System (HPMS) and speed data from Freeway Performance Measurement System (PeMS) as well as transit on board survey and ridership data from L.A. Metro are used. The underlying network in the RTDM includes over 21,000 centerline miles of freeways, arterials and major urban collectors modeled with over 115,000 links (See Fig. 5 for model resolution).

Some of the features of the SCAG RTDM include an auto ownership model, advanced mode and destination choice models, a highly granular 2-tier TAZ (over 11,000 Traffic Analysis Zones in the 6-county SCAG Study Region) system for higher spatial resolution, trip market strata defined by car sufficiency and household income groups used throughout the entire demand models (10 trip purposes), an HDT (Heavy Duty Truck) model, a high-occupancy-vehicle (HOV) diversion model splitting carpool trips from vehicles on the general purpose lanes, and refined–with respect to the earlier model–congestion pricing components. To the authors' knowledge, it has not been utilized for resilience assessments. For detailed discussions regarding the data sources and the modeling efforts related to SCAG RTDM, readers are referred to the model validation report online [74].

In summary, the transportation system analysis module in CRAFT is carried out with the SCAG RTDM which allows the framework to generate resilience insights at a scale and granularity directly translatable to the use of policy makers, practitioners and operators[5]. As mentioned in earlier sections, this underlines the ability of CRAFT to bridge a major gap between transportation resilience research and policy-making. For example, current asset management practices do not account for system resilience while prioritizing maintenance, repair and restoration activities (e.g., bridge maintenance). Deployment of CRAFT could enable decision-makers to integrate data and model-driven resilience assessment into their planning activities. To test CRAFT's capabilities and to explore future directions in its future development (e.g., identifying ad hoc resilience metrics), the authors initiated a collaborative study with District 7 of the California Department of Transportation (Caltrans)[75].

4.3. Resilience at regional economic level

The authors use a multi-regional computable general equilibrium (CGE) model – TERM – to analyze the total economic impacts of and the cost-effectiveness of resilience to seaport and highway transportation network disruptions. A CGE model is a multi-market simulation model based on the simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints (see, e.g., [76], 2011). TERM is a "bottom-up" multi-regional CGE model, meaning that it treats each region as a separate economy and then links regions through commodity imports and exports. The modeling structure of TERM is similar to that of other CGE models. Producers in each region are assumed to minimize production costs subject to a combination of intermediate and primary factor inputs, whose relationship is structured by a series of nested Constant Elasticity of Substitution (CES) functions. A representative household in each region maximizes utility through purchases of optimal bundles of goods in accordance with its preferences and budget constraint. The model was custom built by the research team at the Centre of Policy Studies at Monash University and Victoria University in Australia [77,78]. It was designed specifically for the U.S. on the basis of IMPLAN regional input–output data [79], supplemented by various elasticities gleaned from the latest literature. The TERM database used for this study consists of 97 economic sectors and divides the U.S. economy into three interconnected regions (three-county Southern California Region, Rest of California, and Rest of the U.S.) to examine the spatial spread of disaster impacts.

An important contribution of the CRAFT effort is to develop a methodological linkage between hazard characterization and damage assessment as well as transportation systems analysis modules, and the TERM CGE model. The following steps will be used to enable this modeling linkage: (1) Reduced seaport capacity and damage to general building stocks resulting from the earthquake are determined by FEMA HAZUS[6]; (2) Reductions in commodity supply and demand estimated based on the property damages in Step 1 are fed into the TERM CGE model to determine the general equilibrium impacts (broad multiplier effects including the implications of both quantity and price changes) throughout the region; (3) The transportation systems analysis module specifies the likely re-configuration of freight traffic given physical damage to the network and changes in commodity supply and demand; (4) The increased freight delivery times and distances are converted into increased transportation costs, which are in turn fed into the TERM CGE model to determine the effect on commodity demand and modal choice; (5) An iterative process is used such that the results of the CGE model are fed into the Transportation Network model to re-estimate its results and then fed back to the CGE model, and so on; (6) Various economic resilience tactics (e.g. input conservation, use of inventories, relocation) are fed into the CGE model to estimate the improvements that these tactics can bring about.

In order to analyze the income distribution impacts of the port and transportation network disruptions, we also supplement the TERM

[5] These stakeholders already use the SCAG RTDM in the Greater L.A. Area (counterpart models in other regions) to conform with emissions targets, for asset and investment management including evaluation of new projects, demand management, pricing, etc. [74]. CRAFT, to the authors' knowledge, extends the application scope to (holistic) resilience assessment for the first time.

[6] These inputs are required for the estimation of business interruptions and loss of production and employment. The computer-vision enabled approach applied in the case of bridges is not capable of modeling seaports and buildings. HAZUS is leveraged for this purpose.

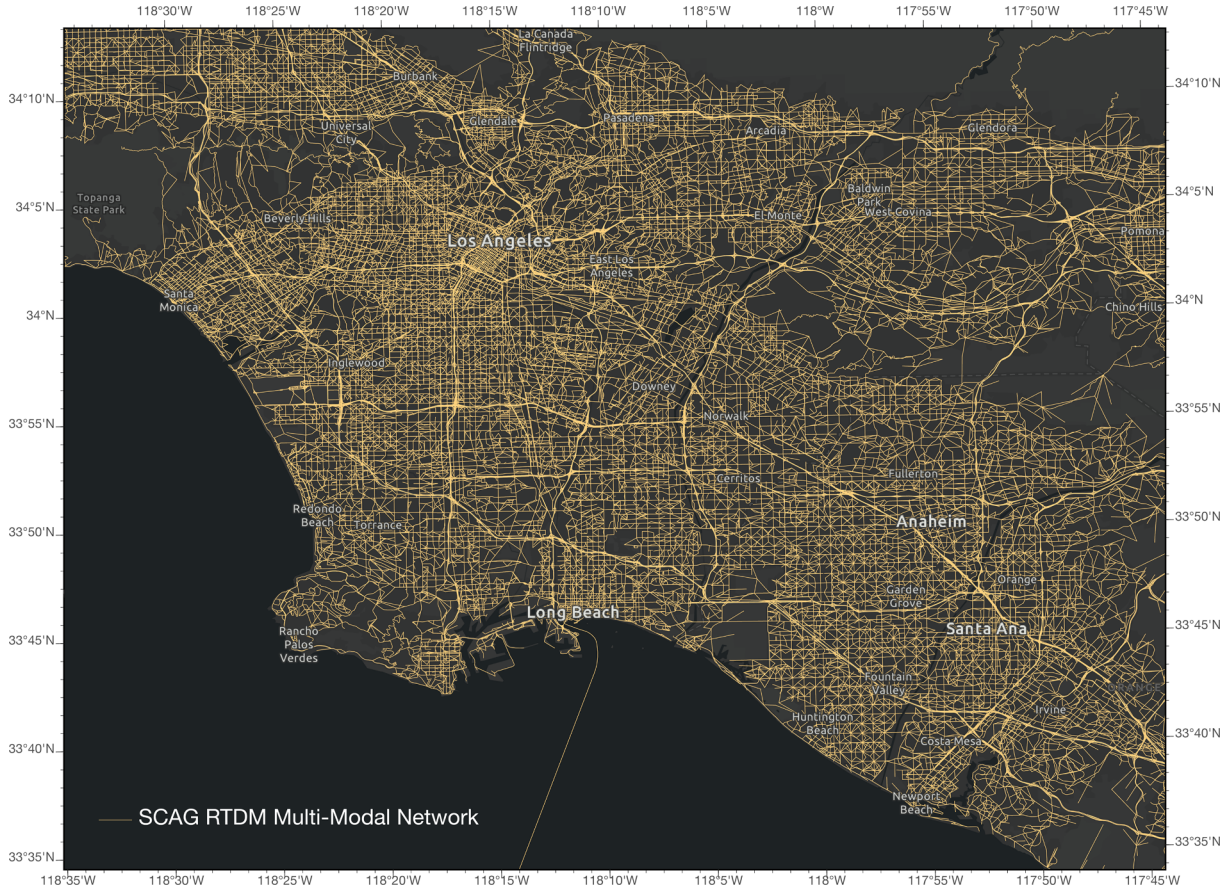


Fig. 5. High resolution, multi-modal network model underlying the SCAG RTDM.

Model with a Multi-Sector Income Distribution Matrix (MSIDM) that provides a basic accounting of income payments across nine income brackets (i.e., what proportion of total personal income paid out by each sector accrues to each income bracket). Following the method developed by Rose et al. [80,81], the MSIDM is constructed using data from the U.S. Bureau of Labor Statistics Occupational Employment Statistics (OES) Division and the U.S. Census. The 2018 California MSIDM was developed using a combination of state and federal tax agency and IMPLAN data.

Linkage of the two aspects of our socioeconomic impact analysis module (the TERM Model and the MSIDM) involves two steps. The first step simply involves multiplying the changes in income in each sector by the income distribution matrix to determine the profile of income changes by bracket associated with the initial earthquake damages, initial changes in transportation patterns, and/or optimal transportation route re-configurations reflecting resilience. The results are summed across sectors to obtain an overall change in income distribution of the economy as a result of the shock. The second step is more complicated, in that it adjusts the MSIDM for changes in two other major factors influencing the income distribution: the changes in capital-labor ratio and changes in factor returns, both of which can be calculated by the TERM Model. This yields a new MSIDM to be applied to the vector of sectoral income changes in a manner similar to that described above. Hence, the bottom-line income distribution impacts are determined by this second set of calculations. The initial distribution and the changed distribution (for both the base case and various resilience cases) can be compared by a number of metrics, such as the Gini coefficient, to determine whether the income distribution has been worsened or improved.

As mentioned, socioeconomic impact analysis associated to the case study results is beyond the scope of this article and will be in the authors' upcoming work. This subsection intended to present discussions on the corresponding CRAFT module for economic impact analysis to provide a holistic view of the multidisciplinary CRAFT effort.

5. Case study: magnitude 7.3 earthquake on Palos Verdes fault

5.1. Hazard characterization

Without losing generality, a scenario earthquake that poses a significant seismic risk to the Ports of Los Angeles and Long Beach (also known as San Pedro Bay port complex) is considered. The port complex forms one of the world's busiest seaport handling more containers per ship call than any other port complex in the world. The complex comprises 32% of the total national market; hence, potential interruptions to its operations bear significance to more than just the City of Los Angeles. In order to quantify the deterministic seismic hazard controlling the area where the port facilities are located, the PSH results from the 2014 version of U.S. Conterminous Seismic Hazard Maps [82] are deaggregated. Based on the deaggregation of the PSH for a 975-year return period period as shown in Fig. 6b, the Palos Verdes fault was found to govern the seismic hazard for the complex. Palos Verdes fault is a predominantly right-lateral strike-slip fault system extending in northwest-southeast direction for more than 100 km [83]. According to the deaggregated hazard results, the moment magnitude with the highest contribution to the overall hazard is determined as 7.3. The Wells-Coopersmith relationship [56] gives a subsurface rupture length of 90.37 km, and a surface rupture length of 71.12 km for a 7.3-moment magnitude reverse-slip fault event. As such, throughout the deterministic hazard calculations conducted for this study, a magnitude 7.3 earthquake generated by rupturing 90.37 km segment of the Palos Verdes fault line is used. Fig. 6a displays the PSHA results for the epicentral location of the defined deterministic event.

In order to simplify that calculation of damages resulting from the

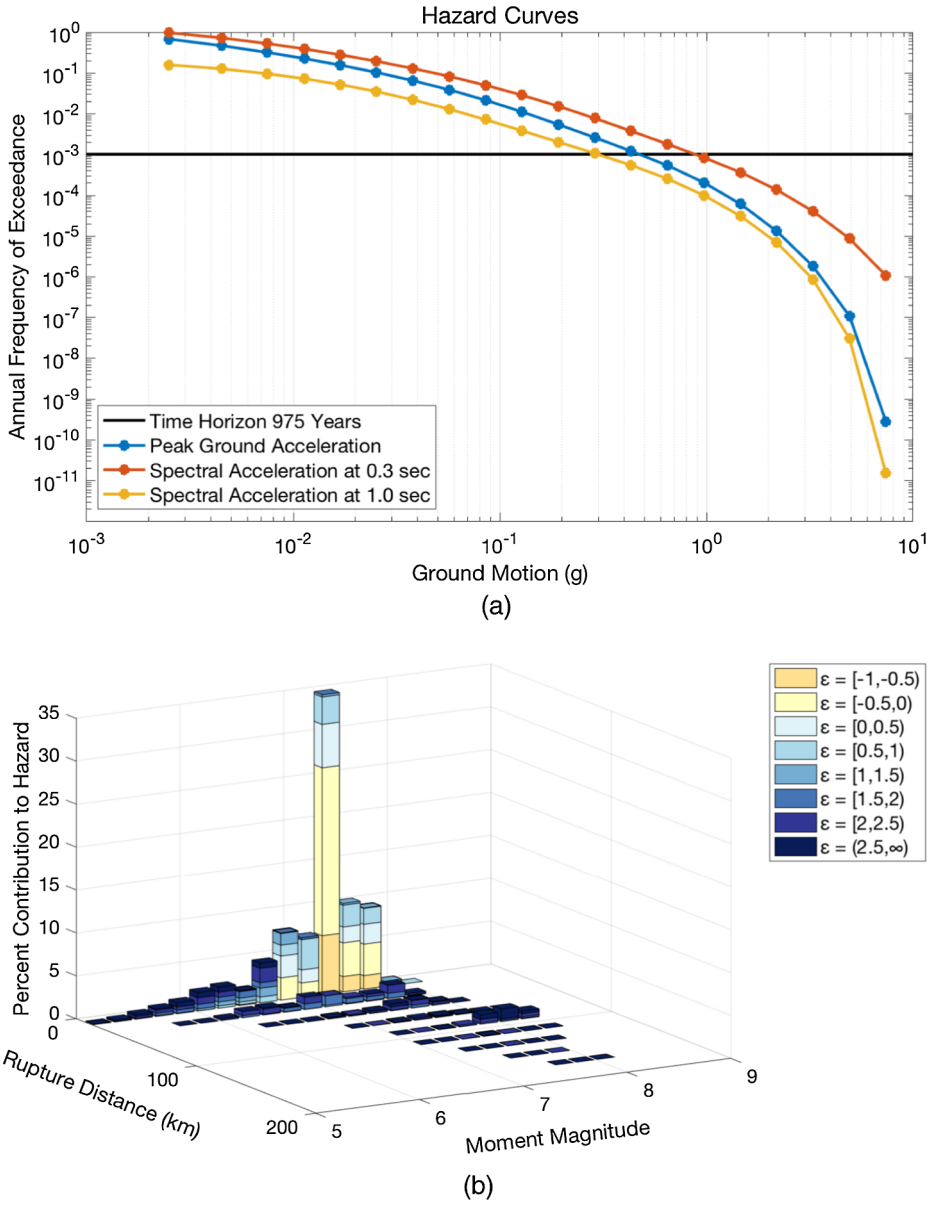


Fig. 6. (a) PSHA results for the Ports of Los Angeles and Long Beach, and (b) their deaggregation.

scenario event, the effect of earthquakes are limited to ground shaking only. Thus, the IMs required for direct damage analyses consisted of 0.3 s and 1.0 s spectral accelerations ($SA_{0.3}$ and $SA_{1.0}$ respectively) for HAZUS predictions and $SA_{1.0}$ and for image-based model predictions for the physical damage. The weighted average of the median SA values computed from 2013 GMPEs by Abrahamson et al., Boore *et al.*, Campbell and Bozorgnia, Chiou and Youngs, and Idriss with weights for the first four equations set to 0.22 and the last one set 0.12. Site effects are taken into account using the slope-based V_{S30} proxy method suggested by Wald, whereas the basin effects were neglected for all site locations. Given the V_{S30} map computed by Thompson *et al.*. [84], and the position of the study region on the Los Angeles basin, both of these assumptions are warranted. Figs. 7a and c show maps of the $SA_{1.0}$ resulting from the scenario event.

5.2. Damage assessment

For the assessment of physical damage, 98 bridges in the immediate periphery of the port complex, i.e., bridges that fall within the region of interest (ROI) in Fig. 8, were modeled using the image-based modeling procedure mentioned above. For the remaining bridges in the area, HAZUS fragility functions [63], created using the 2018 NBI data [67], are utilized. The purpose of this decision is to reduce the considerable computational load required for bridge-specific fragility calculations. The traffic mobility in and out the ports are at large controlled by the functionality of Interstate 110 and 710 and their connections to Interstate 405. Hence, authors assume that simulating just the physical damages for the bridges within the ROI at great detail through the image-based method will yield resiliency metrics with satisfactory accuracy. Authors also realize that, in certain study regions, particular segments of the transportation network may be equipped with extra redundancies, and these redundancies may render defining a representative ROI difficult. When that is the case, the entire bridge inventory within the study region shall be modeled using the image-based approach. (see Fig. 9).

Damage state probabilities for each bridge in the study region are computed using Eq. (4) for ds_1 through ds_5. Subsequently, HAZUS bridge restoration functions [63] and Eq. (5) are utilized to calculate the downtime associated with the defined scenario event. Figs. 7b and d show maps of the computed downtimes. It is observed that the bridge

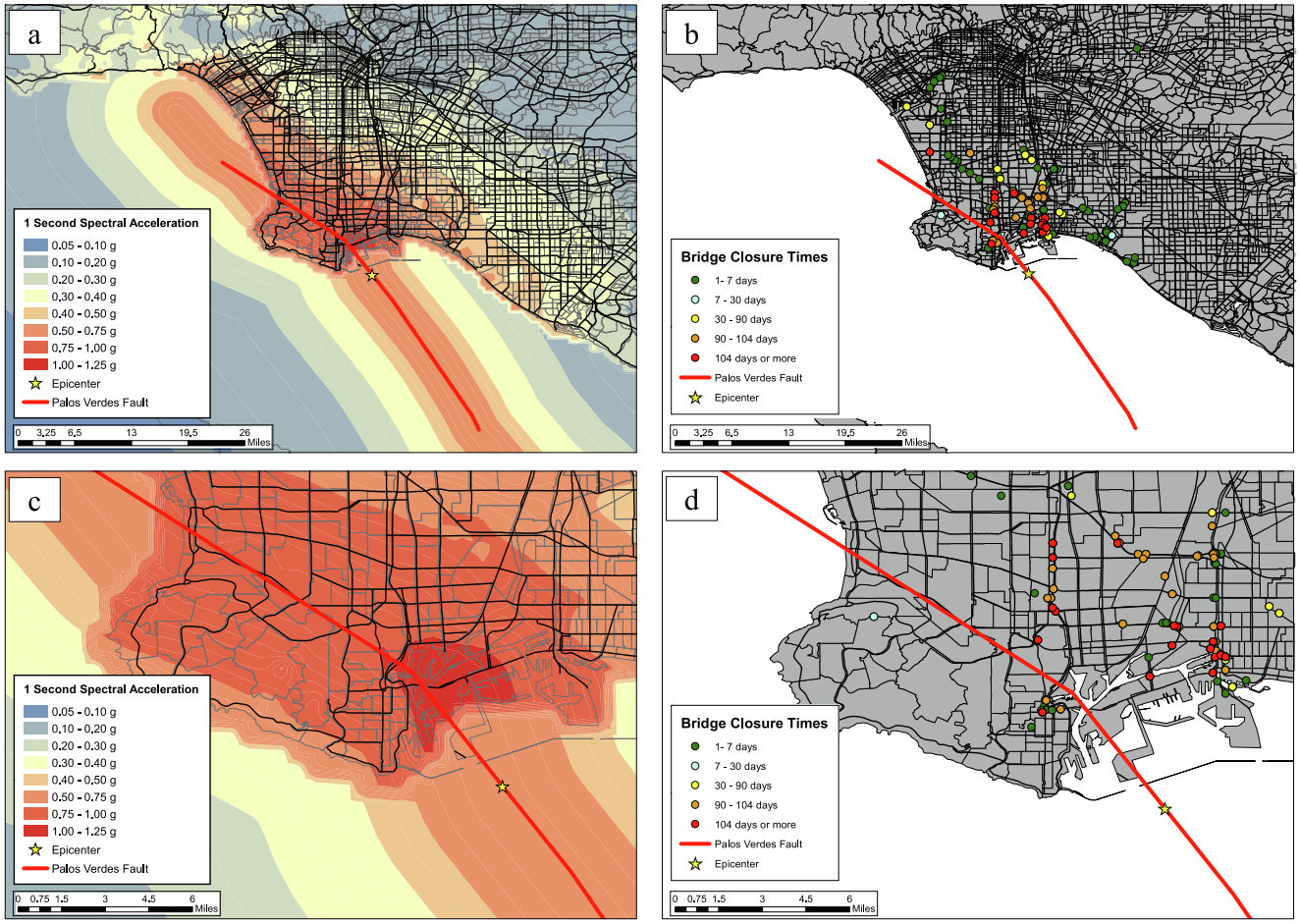


Fig. 7. Deterministic hazard analysis results for 1.0 s spectral accelerations at the general study region level (a), the location of damaged bridges within the general study region (b), 1.0 s spectral acceleration results around rupture length (c), and the corresponding bridge damage in terms of downtimes (d).

downtimes are highest around the rupture port facilities due to the proximity of the scenario event to the complex. However, it is possible to observe bridge closures as far as the Marina Del Rey area. Authors believe that the reason for such damage occurrences is because of the coupled effect of increased ground shaking levels due to the presence of softer soil deposits and pre-1971 construction of the structures.

5.3. Transportation systems analysis

With the damage assessment information for the scenario event, 6 representative network versions (for days 0, 1, 7, 30, 90 and 104) are modeled according to the methodology described in 4.2. to achieve resilience insights at the *system level*. A 75% functionality threshold is determined for the bridge closure policy, i.e. a damaged bridge under recovery is deemed closed to service for the period of time its expected functionality is below 75%. This threshold was adopted from literature [85] due to the lack of standardized data on the relationship between damage or functionality information and closure decisions made by inspectors. This way, 137 bridges are closed to service on day 1, 62 on day 7, 58 on day 30, 45 on day 90 and 19 on day 104. On day 105, full recovery is achieved which brings network functionality back to its pre-disaster baseline level.

Six network topologies are modeled for the mentioned days[7] and bridge closures by manipulating the multi-modal network underlying the SCAG RTDM. This manipulation includes: (1) identifying the links corresponding to the bridges to be closed, (2) modifying and discontinuing the public transit routes crossing those bridges so that the routes carry on serving the remaining portions of the routes, (3) removing the identified links from the network altogether[8]. Consequently, six complete traffic distribution and assignment problems are solved by implementing the transportation systems analysis methodology shown in Fig. 3 to quantify system functionality in pre-disaster and post-disaster settings representing the entire disruption and recovery timeline. In the case study, the authors primarily focus on total travel time indicators *VHT* (Vehicle Hours Traveled) and *Delay* (Vehicle Hours Delayed) since travel time is typically regarded as the primary indicator of utility which makes it the main decision variable of travel behavior. Moreover, total travel distance covered indicators (e.g. *VMT*) may not indicate significant impacts at the *system level* for dense urban networks even for severe disruptions due to the short detours associated with high redundancy networks. Nevertheless, the authors visualize the impacts on vehicle flow and total travel distance (VMT) with maps to demonstrate the reconfiguration of traffic flow due to the disruption (Figs. 12–15).

User-equilibrium results for the 6 network versions allow the quantification of $\Gamma_i(t)$ where $i = VHT$, *Delay* and $t = 0, 1, 7, 30, 90$ and 104 days. Consequently, $Q(t)$ is quantified for all $\Gamma_i(t)$. Figs. 10 and 11 show system functionality, $Q(t)$, based on $\Gamma_{VHT}(t)$ and $\Gamma_{DELAY}(t)$,

[7] The selected days align with the hybrid—image-to-model and HAZUS—damage assessment information and represent the timeline until full recovery in sufficient detail.

[8] Partial closures can be modeled with CRAFT's current capabilities thanks to the detailed model, SCAG RTDM. In this initial work, the authors assume full closure until functionality reaches levels above 75% during recovery.

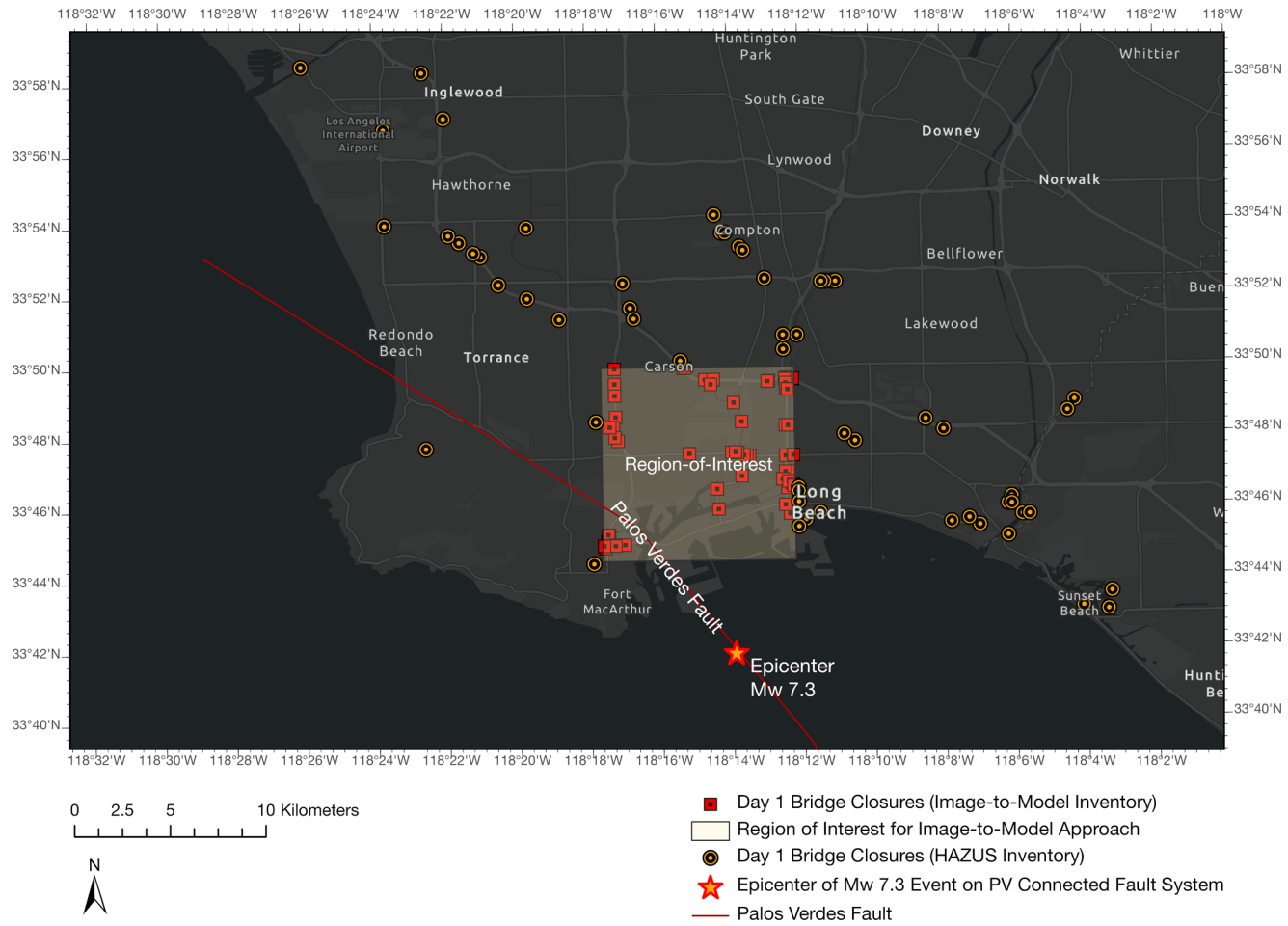


Fig. 8. Modeled bridge closures on Day 1. Region-of-Interest contains bridges modeled with the image-to-model methodology [46].

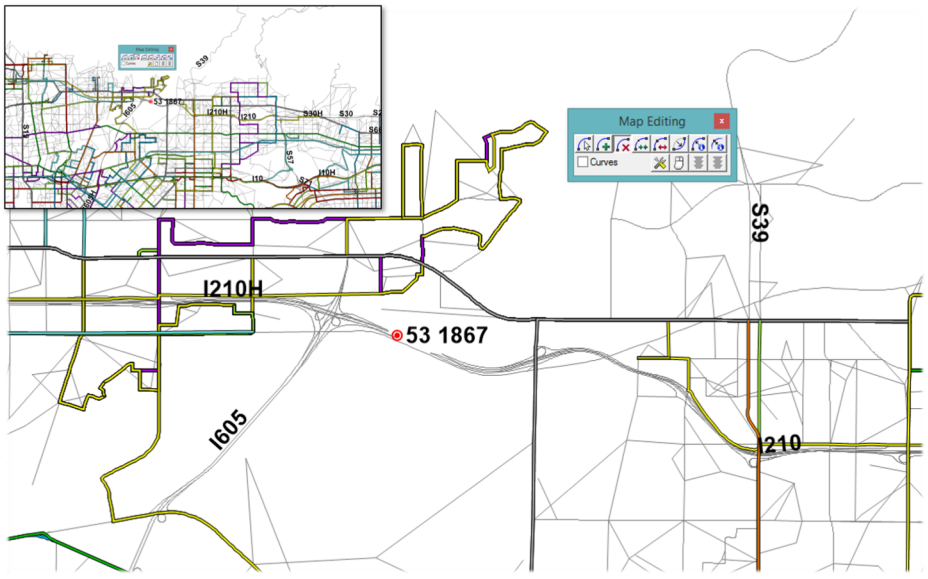


Fig. 9. Network topology manipulation on links corresponding to bridges deemed closed to traffic (e.g., Bridge 53 1867 on I210) implemented with TransCAD's map editing functionalities. Colored, thicker lines indicate public transit routes such as buses, metro, etc. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

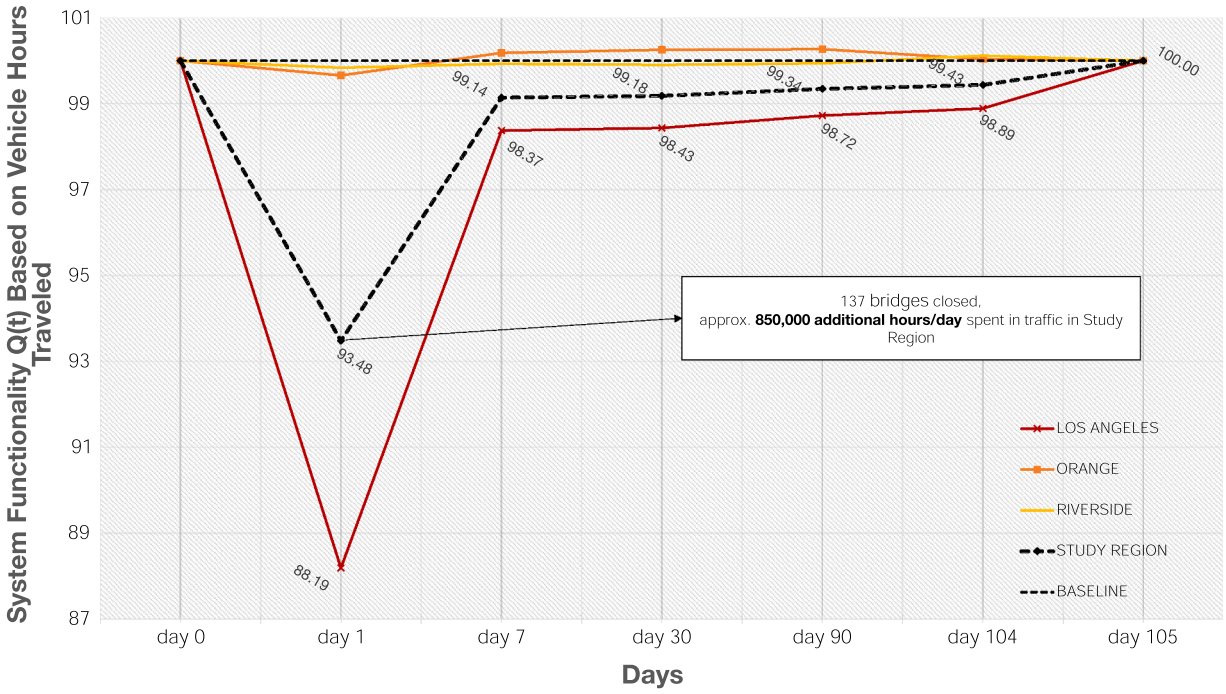


Fig. 10. System functionality $Q(t)$ based on Vehicle Hours Traveled (VHT).

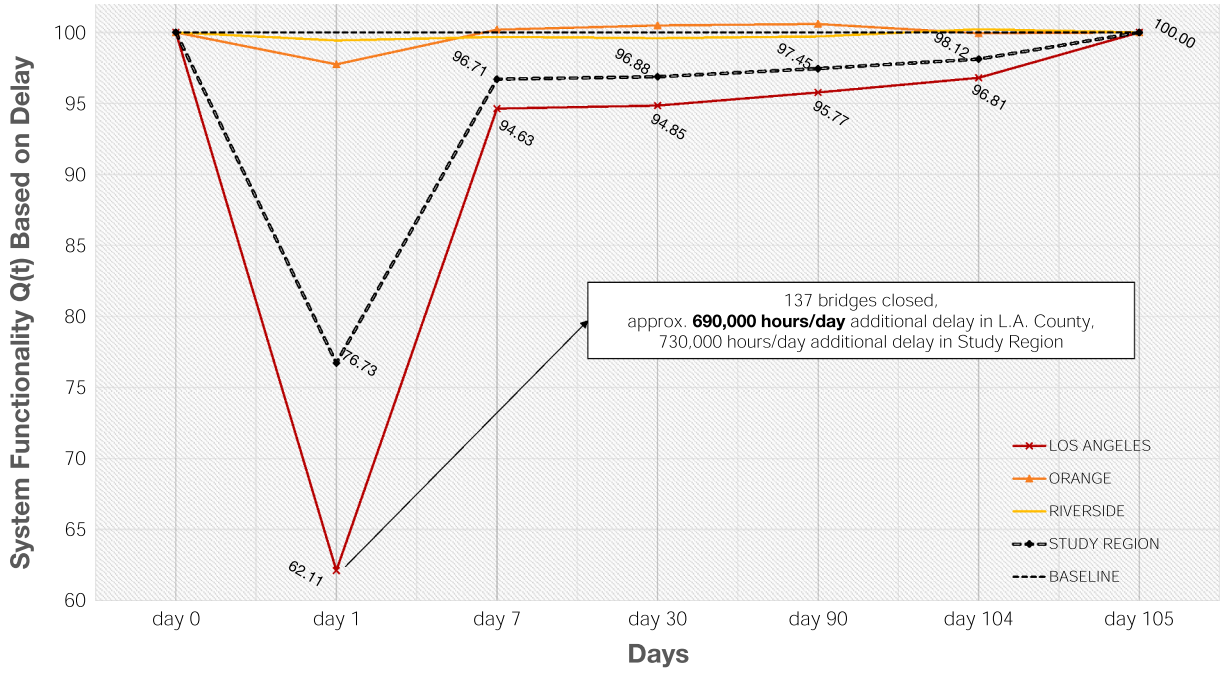


Fig. 11. System functionality $Q(t)$ based on Vehicle Hours Delayed.

respectively[9]. Data are presented for the entire study region as well as the counties of Los Angeles, Orange and Riverside[10].

Significant disruptions in regional mobility is observed, particularly in the Day 1 network in which 137 bridges are deemed closed to service. During the first week, CRAFT estimates a total of approximately 850, 000 hours/day additional travel time spent in traffic which corresponds to a 6.52% decrease in the study region in terms of Γ_{VHT}. As Fig. 10 demonstrates, Los Angeles County burdens most of this functionality loss with a 11.81% loss in functionality.

A visualization of the redistributed vehicle flow—due to the modeled bridge closures—reveals interesting insights. Figs. 12 and 13 illustrate the reconfiguration of vehicle flow during the AM Peak on Days 1 and 7 in terms of percent change relative to the Day 0. In other words, Figs. 12 and 13 illustrate the reconfiguration of vehicle flow after the dramatic loss of functionality on Day 1, and the vehicle flow after a

[9] In Figs. 10 and 11, data points indicate functionality levels on representative days for which a simulation run is carried out. Data points are labeled for lines corresponding to *StudyRegion* and *LosAngeles* only. The linearity in these graphs do not imply a constant rate of system recovery, it is only for visualization purposes to indicate system recovery is still happening even if a full simulation run is not carried out to quantify the exact functionality level on the days between the representative days.

[10] Being further away from the disruption, and due to their relative size and the marginal impacts they experience, Ventura, Imperial and San Bernardino.

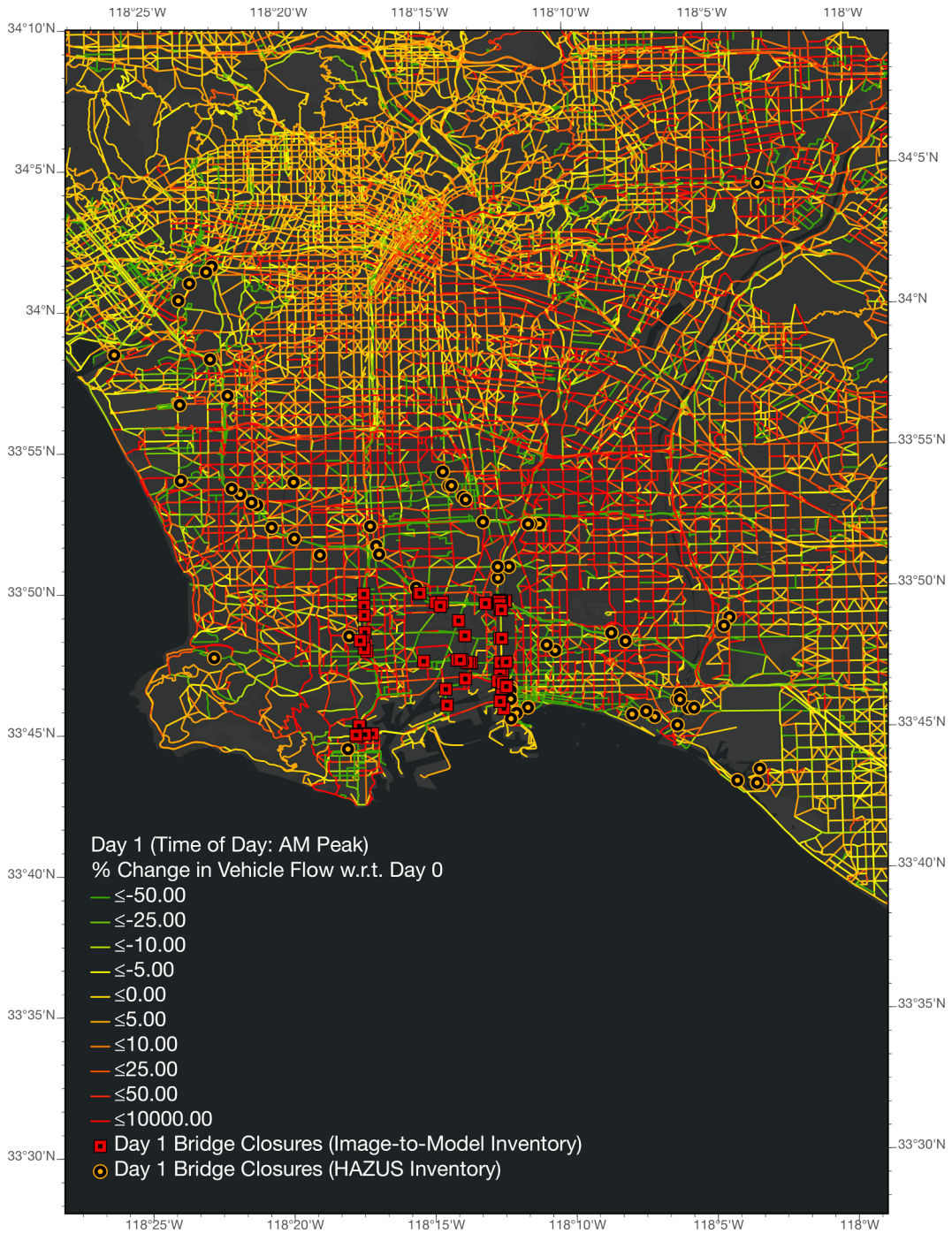


Fig. 12. Changes in vehicle flow from Day 0 to Day 1 after the scenario event during the AM peak. Available online at: https://.arcg.is/HjDO8.

significant portion of system functionality is recovered on Day 7[11]. It is observed that, detouring due to the closed bridges on high volume corridors (e.g., 110, 710, 405 Interstate Highway corridors around the port) shifts the flow to the surface streets, i.e. forces high volume traffic to pass through the neighbourhoods nearby[12]. Same effect is seen during the PM peak which is not included for brevity.

6. Conclusions and future work

The objective of this paper is to present CRAFT, a framework designed by the authors for the comprehensive assessment of resilience in transportation systems. CRAFT advances the research in resilience of transportation systems in 3 directions by: (1) incorporating a novel

[11] ArcGIS suite is used to visualize and share the transportation simulation results obtained with the SCAG RTDM on TransCAD. "Join" functions are employed within Arc Pro to match the tabular data from TransCAD with the spatial network data. This enables rich visualizations of network functionality and the publication of results online (Figs. 12–15). Visualizations and online maps provide vehicle flow and vehicle miles traveled (VMT) results for Days 1 and 7 only where most of the disruption happens. Shared online maps are open to public access and are hosted on a University of Southern California server.

[12] As mentioned in earlier sections, the environmental justice and transportation equity issues related to such effects are not extensively studied in the literature.

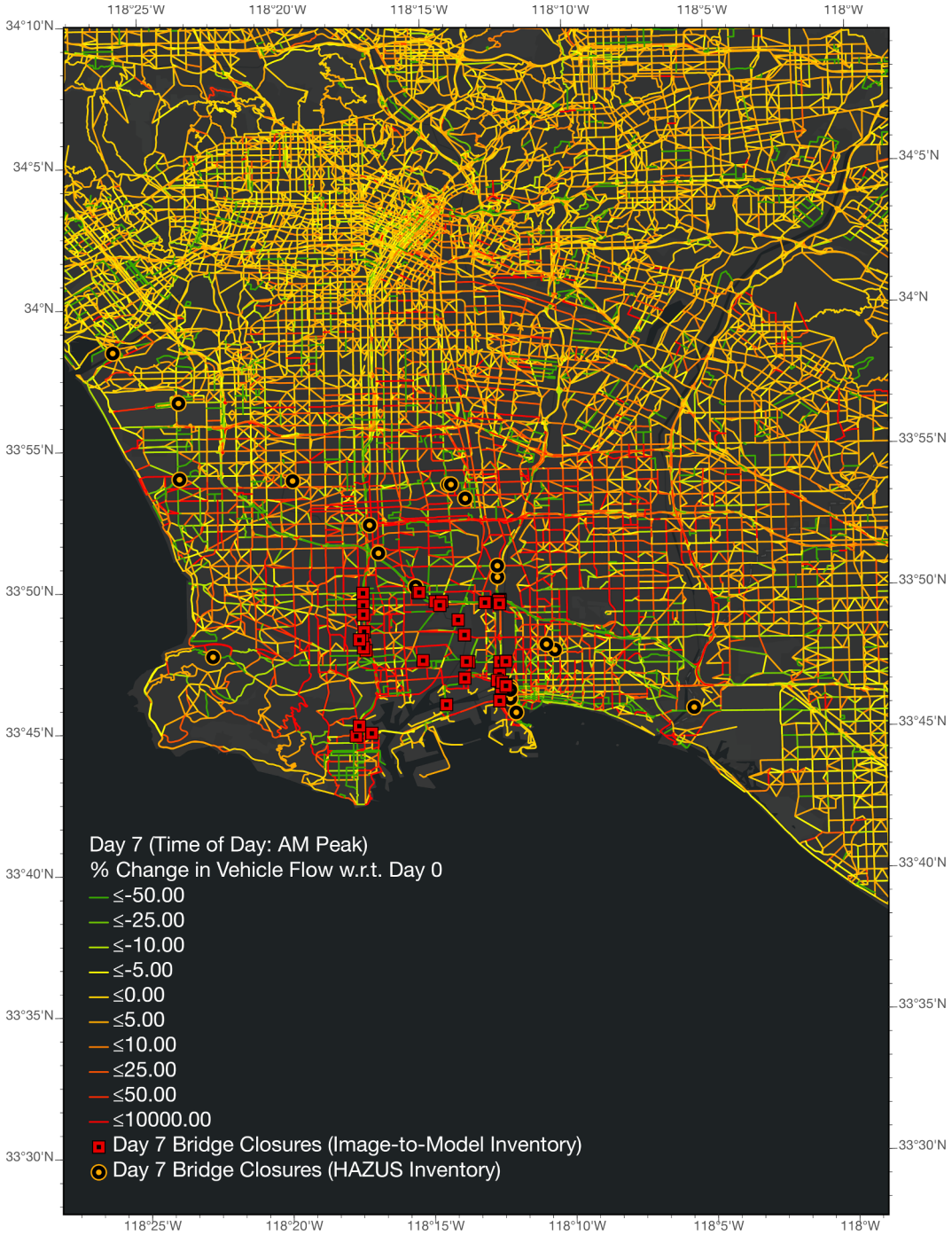


Fig. 13. Changes in Vehicle Flow from Day 0 to Day 7 after the scenario event during the AM peak. Available online at: https://a.rcg.is/1PeDOa.

image-based modeling methodology advancing the regional hazard analysis component beyond the inventories traditionally used in this area, (2) adopting a metropolis-scale travel demand model based on real socioeconomic data to achieve high-fidelity analyses of the transportation system at scale, (3) proposing an advanced socioeconomic impact analysis methodology leveraging a state-of-the-art CGE model informed by the hazard and transportation modules. 2 of the mentioned advancements are demonstrated in this paper through the deployment of CRAFT for a scenario earthquake (M 7.3 Earthquake on Palos Verdes Fault System). Authors' current work is focused on the full integration of CRAFT for a seamless collaboration between its 3 modules.

So far in this research, resilience is conceptualized similar to the static resilience definition by [86] which refers to *using remaining resources efficiently to maintain function*. In the context of CRAFT, static resilience refers to the system-level indicators quantified by the user-equilibrium traffic assignment results under the new network supply conditions in the degraded network specified by the recovery information from hazard analysis. The authors also intend to investigate tactics associated with the concept of *dynamic resilience* defined by Rose and Dormady [86] which is characterized as *investing efficiently in repair and reconstruction in order to reestablish capacity as quickly as possible to regain function*. This entails various resilience tactics that may help the system achieve an improved resilience curve indicated by faster recovery. CRAFT allows the investigation of such tactics, examples including: (1) allocation of resources to more rapidly open critical corridors (e.g., Interstate 405) to service or shifting the heavy duty truck

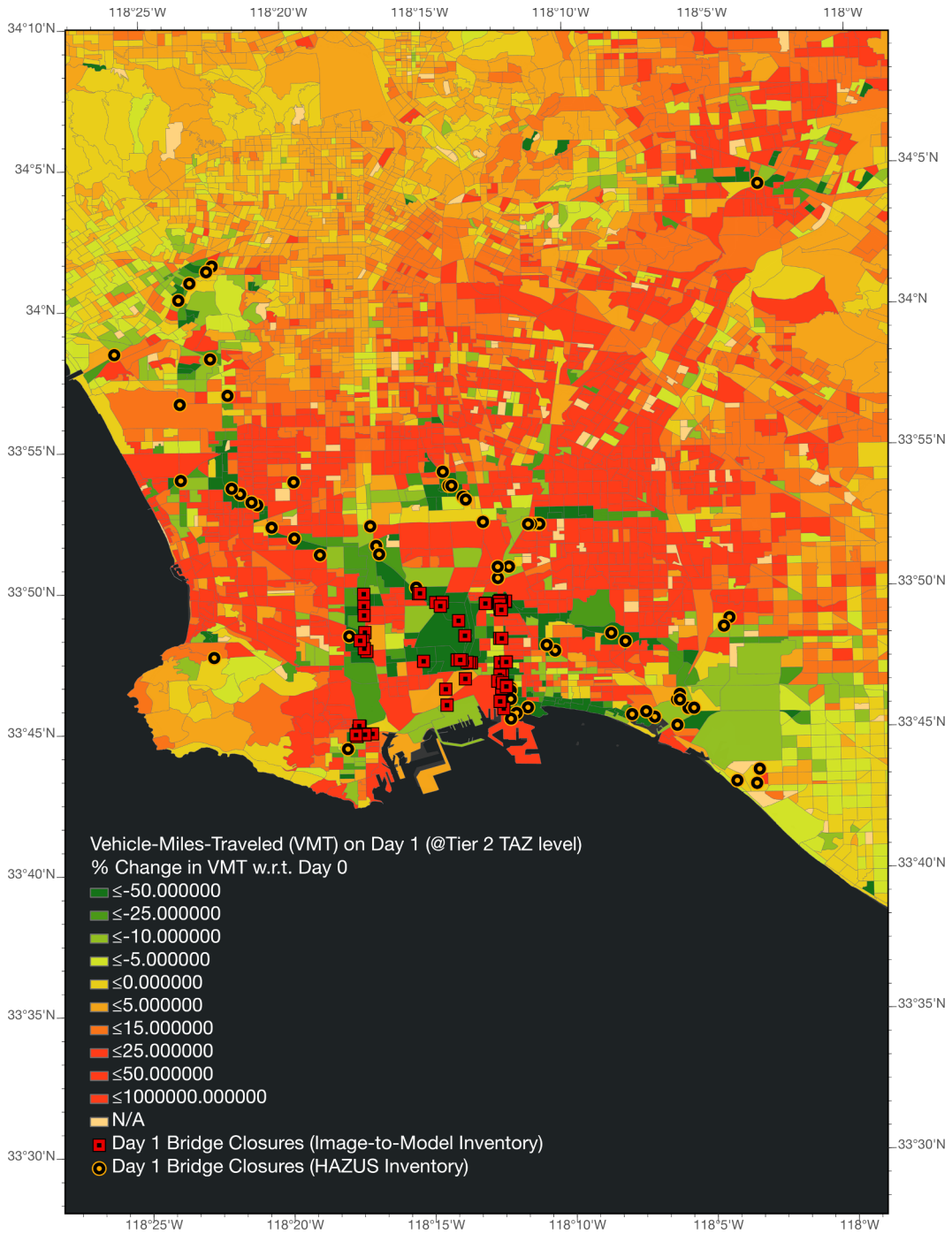


Fig. 14. Spatial distribution of changes in *VMT* from Day 0 to Day 1, aggregated up to Tier 2 TAZ level. Available online at: https://a.rcg.is/1mSC9T.

traffic at the ports to less congested time periods in the day to compensate for less desirable congestion levels due to the hazard, (2) modifications of signal control policies in the major arterials neighboring the closed segments of the freeways that can help facilitate larger volumes of traffic [87], (3) incentives to motivate stay-at-home behavior for commuters to decrease travel demand, and others.

With regards to modeling the post disaster travel behavior to advance CRAFT's deployment beyond the fixed demand assumption made in the case study, the authors have two options. The first option is to make assumptions on behavioral responses such as the stay-at-home (telecommuting) behavior due to reduced network functionality. In this case, the analysis can depend on devised sensitivity scenarios such as *"What if 20% of the home-based-work trips (a commuting trip type in the SCAG RTDM trip market strata) do not happen for a month after the EQ in high impact areas?"*. Stemming from that question, potential improvements in network performance and resilience could be explored with respect to the fixed demand settings. The second option is to use the trip distribution (destination choice) and the mode choice modeling components in CRAFT. Destination choice and mode choice models–apart from the models of home-based-school (college) trips–are based on utility theory with utility functions accommodating terms for travel distance and time parameters [74]. Therefore, these functions can be used to estimate the change in destinations and modes. This can enable insights related to post disaster travel behavior, however, it is essential

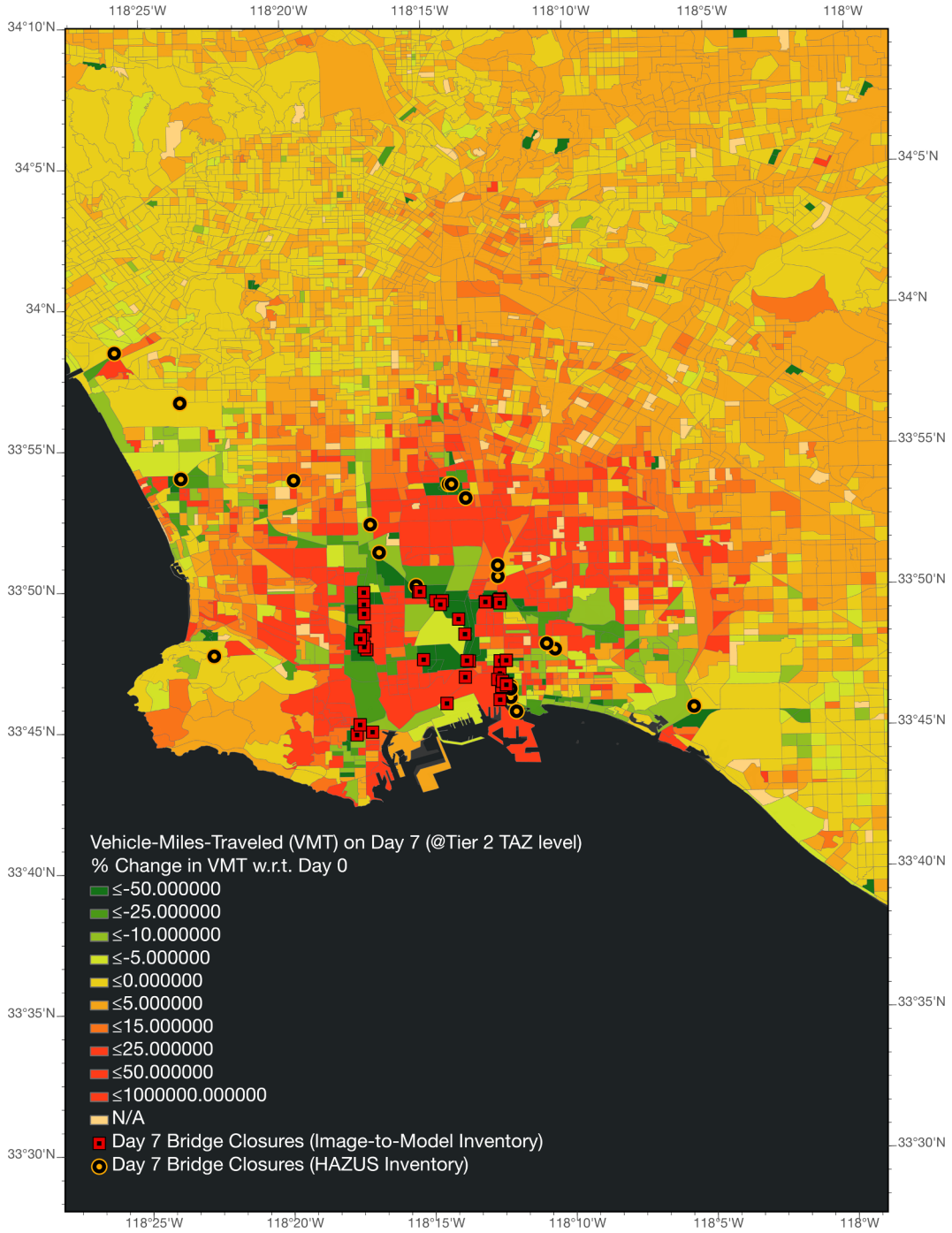


Fig. 15. Spatial distribution of changes in *VMT* from Day 0 to Day 7, aggregated up to Tier 2 TAZ level. Available online at: https://a.rcg.is/1PeDOa.

to note that these results will always be prone to a lack of validation with empirical data[13]. Nevertheless, system-based approaches present the best opportunity for understanding the post-disaster traveler behavior that could unlock more advanced user-centric insights such as demand loss due to disruption, changes in mode and destination choice behaviors, or even longer term decisions on employment, housing, etc.

The authors' future work will investigate the environmental justice and transportation equity aspects of transportation disruptions as well. Environmental justice is an important policy objective. It emphasizes reducing disparities in environmental impacts of economic activity across all segments of the urban society. Transportation equity is a broader concept that deals with concern about disparities across income groups in relation to matters of accessibility and affordability. The CRAFT team intends to extend these concepts of environmental justice and transportation equity to the area of natural hazards that affect transportation systems. In general, the economic and environmental impacts of disasters have been found to fall disproportionately on lower income groups and racial/ethnic minorities. The intention is to examine

[13] Khademi et al. [18] identifies the work of Nagae et al. [38] who take traffic congestion and travelers' route choice behavior into account and performs a UE equilibrium assignment to predict post disaster situation. Nagae et al. [38] admit that whether or not such a static/equilibrium-based assignment is suitable for representing the actual traffic flows on a malfunctioning network after the earthquake is unknown, and emphasize the importance and necessity of further analyses and modeling of post-disaster traffic flows.

the extent to which this is the case for transportation systems disruptions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been supported by NSF Award 1937115 “Convergence Accelerator Phase I (RAISE): Civil Infrastructure Systems Open Knowledge Network (CIS-OKN)” and METRANS/Caltrans grant 65A0674 on “Socioeconomic Dimensions of Resilience to Seaport and Highway Transportation Network Disruptions” as well as The UCLA Institute of Transportation Studies, and the Pacific Earthquake Engineering Research Center (PEER award #1145-NCTRER). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF, METRANS/Caltrans, UCLA ITS, or PEER.

References

[1] United Nations Office for Disaster Risk Reduction, Disaster Statistics, 2018.
[2] United Nations, 68% of the world population projected to live in urban areas by 2050, says UN, 2018.
[3] D. Freckleton, K. Heaslip, W. Louisell, J. Collura, Evaluation of resiliency of transportation networks after disasters, Transp. Res. Rec.: J. Transp. Res. Board 2284 (2012) 109–116.
[4] S. Meerow, J.P. Newell, M. Stults, Defining urban resilience: a review, Landscape Urban Plann. 147 (2016) 38–49.
[5] D.C. Hopkins, J.L. Lumsden, J.A. Norton, Wellington’s lifelines in earthquake project: an outline of a major review, Lifeline Earthquake Engineering, ASCE, 1991, pp. 774–804.
[6] K.J. Tierney, Impacts of Recent U.S. Disasters on Businesses: the 1993 Midwest Floods and the 1994 Northridge Earthquake, in: National Center for Earthquake Engineering Research Conference on the Economic Impacts of Catastrophic Earthquakes, 1995, pp. 189–222.
[7] S.E. Chang, Transportation planning for disasters: an accessibility approach, Environ. Plann. A 35 (2003) 1051–1072.
[8] ASCE, Infrastructure Report Card, Technical Report, American Society of Civil Engineers, 2017.
[9] A. Reggiani, Network resilience for transport security: Some methodological considerations, Transp. Policy 28 (2013) 63–68.
[10] A.A. Ganin, M. Kitsak, D. Marchese, J.M. Keisler, T. Seager, I. Linkov, Resilience and efficiency in transportation networks, Sci Adv. 3 (2017) 1–9.
[11] S. Kaplan, B.J. Garrick, On the quantitative definition of risk, Risk Anal. 1 (1981) 11–27.
[12] K. Berdica, An introduction to road vulnerability: what has been done, is done and should be done, Transp. Policy 9 (2002) 117–127.
[13] M. Bruneau, S.E. Chang, R.T. Eguchi, G.C. Lee, T.D. O’Rourke, A.M. Reinhorn, M. Shinozuka, K. Tierney, W.A. Wallace, D. Von Winterfeldt, A framework to quantitatively assess and enhance the seismic resilience of communities, Earthquake Spectra 19 (2003) 733–752.
[14] E. Hollnagel, Prologue: The scope of resilience engineering, 2011.
[15] L.G. Mattsson, E. Jenelius, Vulnerability and resilience of transport systems – a discussion of recent research, Transp. Res. Part A: Policy Pract. 81 (2015) 16–34.
[16] R. Faturechi, E. Miller-Hooks, Measuring the performance of transportation infrastructure systems in disasters: a comprehensive review, J. Infrastruct. Syst. 21 (2014) 04014025.
[17] A. Rose, Defining and measuring economic resilience to earthquakes, Disaster Prevent. Manage. 13 (2004) 307–314.
[18] N. Khademi, B. Balaei, M. Shahri, M. Mirzaei, B. Sarrafi, M. Zahabiun, A.S. Mohaymany, Transportation network vulnerability analysis for the case of a catastrophic earthquake, Int. J. Disaster Risk Reduct. 12 (2015) 234–254.
[19] E. Koc, B. Cetiner, L. Soibelman, E. Taciroglu, System-based vulnerability and resilience assessment in mega-scale transportation systems: towards data and model-driven methodologies, in: Proceedings of the ASCE Computing in Civil Engineering Conference, 2019, pp. 444–450.
[20] A. Nicholson, Z.-P. Du, Degradable transportation equilibrium alan nicholson systems: an integrated model, Transp. Res. Part B 31 (1997) 209–223.
[21] P.M. Murray-Tuite, H.S. Mahmassani, Methodology for determining vulnerable links in a transportation network, Transp. Res. Rec.: J. Transp. Res. Board 2004 (1882) 88–96.
[22] D.M. Scott, D.C. Novak, L. Aultman-Hall, F. Guo, Network Robustness Index: a new method for identifying critical links and evaluating the performance of transportation networks, J. Transp. Geogr. 14 (2006) 215–227.
[23] J.L. Sullivan, D.C. Novak, L. Aultman-Hall, D.M. Scott, Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: a link-based capacity-reduction approach, Transp. Res. Part A: Policy Pract. 44 (2010) 323–336.
[24] A. Nagurney, A network efficiency measure for congested networks, Europhys. Lett. 71 (2007) 1–5.
[25] M.A. Taylor, S.V. Sekhar, G.M. D’Este, Application of accessibility based methods for vulnerability analysis of strategic road networks, Netw. Spatial Econ. 6 (2006) 267–291.
[26] A. Chen, C. Yang, S. Kongsomsaksakul, M. Lee, Network-based acessibility measures for vulnerability analysis of degradable transportation networks, Netw. Spatial Econ. 7 (2007) 241–256.
[27] B. Cetiner, E. Koc, L. Soibelman, E. Taciroglu, E.J. Lee, A. Nutakki, A granular simulation of bridge closures due to a southern california scenario earthquake and its effects on the disruption and recovery of freight traffic to and from ports of los angeles and long beach, in: Proceedings of the 2019 ASCE International Conference on Sustainable Infrastructure, pp. 575–585.
[28] F. Bono, E. Gutiérrez, A network-based analysis of the impact of structural damage on urban accessibility following a disaster: the case of the seismically damaged Port Au Prince and Carrefour urban road networks, J. Transp. Geogr. 19 (2011) 1443–1455.
[29] F. Wei, E. Koc, L. Soibelman, N. Li, Disaster economics and networked transportation infrastructures: status quo and a multi-disciplinary framework to estimate economic losses, in: Workshop of the European Group for Intelligent Computing in Engineering, Springer, pp. 3–22.
[30] A. Kiremidjian, J. Moore, Y.Y. Fan, N. Basoz, O. Yazali, M. Williams, Highway Demonstration Project, Peer Report 2006/02, Technical Report, Pacific Earthquake Engineering Research Center, 2006.
[31] S. Fabozzi, E. Bilotta, M. Picozzi, A. Zollo, Feasibility study of a loss-driven earthquake early warning and rapid response systems for tunnels of the italian high-speed railway network, Soil Dyn. Earthquake Eng. 112 (2018) 232–242.
[32] J.-S. Jeon, R. DesRoches, T. Kim, E. Choi, Geometric parameters affecting seismic fragilities of curved multi-frame concrete box-girder bridges with integral abutments, Eng. Struct. 122 (2016) 121–143.
[33] F. Soleimani, S. Mangalathu, R. DesRoches, A comparative analytical study on the fragility assessment of box-girder bridges with various column shapes, Eng. Struct. 153 (2017) 460–478.
[34] HAZUS-MH, Earthquake loss estimation methodology, National Institute of Building Sciences for Federal Emergency Management Agency, Washington, DC, MR3 Edition, 2008.
[35] C.A. Kircher, R.V. Whitman, W.T. Holmes, Hazus earthquake loss estimation methods, Nat. Hazards Rev. 7 (2006) 45–59.
[36] E. Thompson, D.J. Wald, C. Worden, Avs 30 map for california with geologic and topographic constraints, Bull. Seismol. Soc. Am. 104 (2014) 2313–2321.
[37] E. Koc, B. Cetiner, J. Lee, A. Nutakki, L. Soibelman, E. Taciroglu, System-based resilience assessment of networked transportation systems in metropolitan areas: Case of greater los angeles, in, Proceedings of the 26th International Workshop on Intelligent Computing in Engineering, 2019.
[38] T. Nagae, T. Fujihara, Y. Asakura, Anti-seismic reinforcement strategy for an urban road network, Transp. Res. Part A: Policy Pract. 46 (2012) 813–827.
[39] Y. Asakura, Requirements for transport network flow models used in reliability analysis, Int. J. Critical Infrastruct. 3 (2007) 287–300.
[40] A.J. Nicholson, Road network unreliability: impact assessment and mitigation, Int. J. Crit. Infrastruct. 3 (2007) 346–375.
[41] F. Wei, E. Koc, L. Soibelman, N. Li, Disturbances to urban mobility and comprehensive estimation of economic losses, Polytechnica (2018).
[42] A. Rose, Economic principles, issues, and research priorities in hazard loss estimation, Modeling Spatial and Economic Impacts of Disasters, Springer, 2004, pp. 13–36.
[43] S. Cho, P. Gordon, J.E. Moore, H.W. Richardson, M. Shinozuka, S. Chang, Integrating transportation network and regional economic models to estimate the costs of a large urban earthquake, J. Regional Sci. 41 (2001) 39–65.
[44] R. Lu, I. Brilakis, C.R. Middleton, Detection of structural components in point clouds of existing rc bridges, Comput.-Aided Civil Infrastruct. Eng. 34 (2019) 191–212.
[45] G. Morgenthal, N. Hallermann, J. Kersten, J. Taraben, P. Debus, M. Helmrich, V. Rodehorst, Framework for automated uas-based structural condition assessment of bridges, Automat. Construct. 97 (2019) 77–95.
[46] B. Cetiner, Image-Based Modeling of Bridges and Its Applications to Evaluating Resiliency of Transportation Networks, Ph.D. thesis University of California, Los Angeles, Los Angeles, CA, 2020.
[47] S. Mangalathu, Performance based Grouping and Fragility Analysis of Box-girder Bridges in California, Ph.D. thesis Georgia Institute of Technology, 2017.
[48] A. Rose, F. Prager, Z. Chen, S. Chatterjee, D. Wei, N. Heatwole, E. Warren, Economic Consequence Analysis of Disasters: The E-CAT Software Tool, Springer, 2017.
[49] H. Lofgren, S. Robinson, Spatial-network, general-equilibrium model with a stylized application, Regional Sci. Urban Econ. 32 (2002) 651–671.
[50] Z. Chen, A. Rose, Economic resilience to transportation failure: a computable general equilibrium analysis, Transportation 45 (2018) 1009–1027.
[51] K. Schumacher, R.D. Sands, Where are the industrial technologies in energy-economy models? An innovative CGE approach for steel production in Germany, Energy Econ. 29 (2007) 799–825.
[52] A. Rose, S.-Y. Liao, Modeling regional economic resilience to disasters: a computable general equilibrium analysis of water service disruptions*, J. Regional Sci. 45 (2005) 75–112.
[53] M.A. Goldberg, On the inefficiency of being efficient, Environ. Plann. A: Econ.

Space 7 (1975) 921–939.
[54] R.K. McGuire, Probabilistic seismic hazard analysis and design earthquakes: closing the loop, Bull. Seismol. Soc. Am. 85 (1995) 1275–1284.
[55] P. Bazzurro, C.A. Cornell, Disaggregation of seismic hazard, Bull. Seismol. Soc. Am. 89 (1999) 501–520.
[56] D.L. Wells, K.J. Coppersmith, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seismol. Soc. Am. 84 (1994) 974–1002.
[57] J.P. Stewart, D.M. Boore, E. Seyhan, G.M. Atkinson, NGA-West2 equations for predicting vertical-component PGA, PGV, and 5%-damped PSA from shallow crustal earthquakes, Earthquake Spectra 32 (2016) 1005–1031.
[58] PEER, NGA-East: Median Ground-Motion Models for the Central and Eastern North America Region, Technical Report Peer Report 2015/04, Pacific Earthquake Engineering Research Center, Berkeley, CA, 2015.
[59] K. Mackie, B. Stojadinović, Probabilistic seismic demand model for california highway bridges, J. Bridge Eng. 6 (2001) 468–481.
[60] J.E. Padgett, B.G. Nielson, R. DesRoches, Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios, Earthquake Eng. Struct. Dyn. 37 (2008) 711–725.
[61] S. Argyroudis, K. Pitilakis, Seismic fragility curves of shallow tunnels in alluvial deposits, Soil Dyn. Earthquake Eng. 35 (2012) 1–12.
[62] A. Kiremidjian, J. Moore, Y.Y. Fan, N. Basoz, O. Yazali, M. Williams, Highway Demonstration Project, Technical Report Peer Report 2006/02, Pacific Earthquake Engineering Research Center, Berkeley, CA, 2006.
[63] FEMA, Hazus-MH 2.1 Technical Manual: Earthquake Model, Federal Emergency Management Agency, Washington, DC, 2003.
[64] NIBS, A Guide to Using HAZUS for Mitigation, Technical Report, Federal Emergency Management Agency, Reston, VA, 2002.
[65] FEMA, FEMA 433: Using HAZUS-MH for Risk Assessment, Technical Report, Federal Emergency Management Agency, Reston, VA, 2004.
[66] OpenStreetMap contributors, Planet dump retrieved from https://planet.osm.org, https://www.openstreetmap.org, 2019.
[67] FHWA, Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, Technical Report FHWA-PD-96-001, Department of Transportation, Federal Highway Administration, Washington, D.C., 1995.
[68] USGS, Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, https://doi.org/10.5066/F7PR7TFT, 2015.
[69] D. Vamvatsikos, C.A. Cornell, Incremental dynamic analysis, Earthquake Eng. Struct. Dyn. 31 (2002) 491–514.
[70] J.W. Baker, T. Lin, S.K. Shahi, N. Jayaram, New Ground Motion Selection Procedures and Selected Motions for the PEER Transportation Research Program, Technical Report March, Pacific Earthquake Engineering Research Center (PEER), Berkeley, CA, 2011.
[71] K. Ramanathan, J.E. Padgett, R. DesRoches, Temporal evolution of seismic fragility curves for concrete box-girder bridges in California, Eng. Struct. 97 (2015) 29–46.
[72] D. Wei, E. Koc, A. Rose, Z. Chen, L. Soibelman, Socioeconomic Dimensions of Resilience to Seaport and Highway Transportation Network Disruptions, Technical Report, Pacific Southwest Region University Transportation Center, 2020.
[73] D. Frangopol, P. Bocchini, Resilience as optimization criterion for the rehabilitation of bridges belonging to a transportation network subject to earthquake, Struct. Congress (2011) 2044–2055.
[74] Southern California Association of Governments, Regional Transportation Plan, 2019.
[75] National Science Foundation, Convergence accelerator phase 1 (RAISE): Civil infrastructure systems open knowledge network (CIS-OKN), 2019.
[76] M.E. Burfisher, Introduction to Computable General Equilibrium Models, Cambridge University Press, 2017.
[77] G. Wittwer, Economic Modeling of Water: the Australian CGE Experience vol. 3, Springer Science & Business Media, 2012.
[78] V.U. Center of Policy Studies (CoPS), The TERM Model, 2019.
[79] M.I. Group, Impact Analysis for Planning (IMPLAN) System, 2012.
[80] A.Z. Rose, B. Stevens, G. Davis, Natural Resource Policy and Income Distribution, Johns Hopkins Univ Pr, 1988.
[81] A. Rose, D. Wei, F. Prager, Distributional impacts of greenhouse gas emissions trading: alternative allocation and recycling strategies in california, Contemp. Econ. Policy 30 (2012) 603–617.
[82] M.D. Petersen, M.P. Moschetti, P.M. Powers, C.S. Mueller, K.M. Haller, A.D. Frankel, Y. Zeng, S. Rezaeian, S.C. Harmsen, O.S. Boyd, N. Field, R. Chen, K.S. Rukstales, N. Luco, R.L. Wheeler, R.A. Williams, A.H. Olsen, Documentation for the 2014 Update of the United States National Seismic Hazard Maps, Technical Report, U.S. Geological Survey, Reston, VA, 2014.
[83] D.S. Brothers, J.E. Conrad, K.L. Maier, C.K. Paull, M. McGann, D.W. Caress, The Palos Verdes fault offshore Southern California: Late Pleistocene to present tectonic geomorphology, seascape evolution, and slip rate estimate based on AUV and ROV surveys, J. Geophys. Res.: Solid Earth 120 (2015) 4734–4758.
[84] E.M. Thompson, D.J. Wald, C.B. Worden, A VS30Map for California with geologic and topographic constraints, Bull. Seismol. Soc. Am. 104 (2014) 2313–2321.
[85] P. Gordon, J.E. Moore II, H.W. Richardson, M. Shinozuka, D. An, S. Cho, Earthquake disaster mitigation for urban transportation systems: an integrated methodology that builds on the kobe and northridge experiences, Model. Spatial Econ. Impacts Disasters (2004) 205–232.
[86] A. Rose, N. Dormady, Advances in analyzing and measuring dynamic economic resilience, SSRN Electron. J. 2 (2018) 1–8.
[87] P. Hosseini, K. Savla, A comparison study between proportionally fair and max pressure controllers for signalized arterial networks, in: TRB 95th Annual Meeting Compendium of Papers, Transportation Research Board, 2016.