Socioeconomic Dimensions of Resilience to Seaport and Highway Transportation Network Disruptions

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16. Abstract

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The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

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Abstract

The economic impacts of a major disruption to seaports and their associated transportation infrastructure can be extensive and can affect people in a region unequally. To estimate the aggregate and distributional economic consequences of such disruptions, we developed an integrated transportation-socioeconomic analysis model to analyze the impacts of port and transportation network disruptions and the effectiveness of resilience tactics across socioeconomic income groups. The integrated model is applied to a simulated earthquake scenario that affects the Ports of Los Angeles and Long Beach and their associated inland highway freight transportation network.

The total GDP losses stemming from port disruptions, hinterland transportation cost increases, and general building damages from the simulated earthquake scenario are estimated to be $20.7 billion in the Los Angeles Metro Region and $25.8 billion in the U.S. Various resilience tactics can help reduce the GDP impacts to $12.1 billion in LA and $11 billion in the U.S., representing a loss reduction of 41.3% and 57.6%, respectively. The lower level of impacts on the U.S. economy as a whole is due to a shift of economic activity to areas outside of California, representing a GDP increase of $1.3 billion in Rest of the U.S. The distributional analyses indicate that the percentage impacts are a relatively higher proportion of income for the lower- to middle-income groups for port disruptions, but are higher for the middle- and higher-income groups for general building damages.

List of Acronyms

BEA: United States Bureau of Economic Analysis
BI: Business Interruption
BLS: United States Bureau of Labor Statistics
CES: Constant Elasticity of Substitution
CGE: Computable General Equilibrium
Delay: Vehicle-Hours-Delayed
FEMA: Federal Emergency Management Agency
GDP: Gross Domestic Product
HDT: Heavy Duty Truck
HOV: high-occupancy-vehicle HOV
HTS: Harmonized Tariff Schedule
IIR: Inherent Resilience (input substitution, import substitution, and production activity relocation)
LOS: Level-of-service
MSIDM: Multi-sector Income Distribution Matrix
NAICS: North America Industry Classification System
NRI: Network Robustness Index
OES: Occupational Employment Statistics
PeMS: Freeway Performance Measurement System
SCAG RTDM: Southern California Association of Governments Regional Travel Model
SCAG: Southern California Association of Governments
SER: Static Economic Resilience
TAZ: Traffic Analysis Zone
TERM: The Enormous Regional Model
TTD: Total Travel Distance
TTT: Total Travel Time
VHT: Vehicle-Hours-Traveled
VMT: Vehicle-Miles-Traveled
UE: User Equilibrium

Socioeconomic Dimensions of Resilience to Seaport and Highway Transportation Network Disruption

Executive Summary

Serving as critical portals of a nation's supply-chain, seaports and their associated transportation infrastructure are especially vulnerable to major disruptions from a variety of causes. The economic impacts of these disasters can be extensive well beyond the on-site operations at the port complex, through the supply-chain effects of the disruptions and/or delays of delivering imports and exports from ports to their destinations and vice versa. Many studies have estimated the direct and indirect impacts of transportation network disruptions in general and port disruptions in particular, and found them to be quite significant. However, most of the economic impact analysis methods and models in the existing literature focus on a single infrastructure component (airport, seaport, bridge, etc.), and fail to incorporate the spatially distributed and network nature of transportation infrastructures. In addition, there are only a handful of studies adequately considered and factored in the effect of resilience in the economic impact modeling of port and transportation network disruptions. Moreover, disasters and their impacts on critical infrastructure do not affect all people in a region equally. Studies have shown that the poor are typically affected proportionally more in relation to their personal incomes than are those in middle- and upper-income brackets.

To estimate the aggregate and distributional economic consequences of such disasters, we developed a linked regional transportation network model and a multi-regional computable general equilibrium (CGE) model (the TERM CGE Model). In addition, we also evaluate the role of resilience -- ways to reduce the impacts of disruptions to imports and exports through such tactics as input substitutions, use of inventories, conservation, rescheduling of economic activities, as well as to reduce the impacts of transportation network degradations through more rapid opening of critical corridors. We also integrated a multi-sector income distribution matrix (MSIDM) into the modeling framework to analyze the impacts of port and transportation network disruptions and the effectiveness of resilience tactics across socioeconomic income groups.

The analysis results of the simulated earthquake scenario indicate that it takes 150 days for the ports to fully recover from the simulated disaster. The total GDP impacts stemming from both import and export disruptions are estimated to be $11.8 billion in the LA Metro Region and $67.5 billion for the U.S. before resilience. These impacts are reduced to $1.5 billion and $9.4 billion for the LA Metro and the U.S., respectively, after we take into consideration three major types of inherent economic resilience (input substitution, import substitution, and regional production shifts) that are automatically captured by the TERM CGE Model. After we consider the other types of inherent resilience tactics and adaptive resilience tactics, the total impacts are further reduced to $0.24 billion in the LA Metro Region and $0.65 billion in the U.S. In addition, the damage to the highway transportation system also causes a 0.53% increase in truck transportation cost within the LA Metro Region and a 0.26% increase between LA Metro Region and Rest of CA (on an annual basis). The estimated GDP losses caused by the truck transportation cost increases are only $15 million in the LA Metro Region because of the high redundancy of the transportation network. The simulated seismic events also result in damages to the

general building stock, with total GDP losses estimated to be $19.2 billion in LA Metro and $16.5 billion in the U.S. with no resilience. The impacts are reduced to $11.8 billion for LA and $10.1 billion for the U.S. after the adjustment for resilience. The lower impacts at the national level are due to the offsetting effect stemming from regional production shifts from the earthquake impacted region to other regions in the country. The combined simulation of all three types of disruptions/damages yields GDP losses of $12.1 billion for the LA Metro Region and $10.9 billion for the U.S. after we consider all the relevant resilience tactics. The loss reduction potential of resilience is 41.3% at the regional level of LA and 57.6% at the national level.

The income distribution analyses for the LA Metro Region indicate that the income losses stemming from port disruptions are born slightly disproportionately by lower- and middle-income groups. The Resilience Case for port disruptions results in a Gini coefficient that is slightly lower than the baseline level (indicating a more equitable distribution of income), which is explained by the fact that the various resilience tactics are more effective in reducing the impacts in the sectors that employ relatively more people from lower-income groups. The Gini coefficients of the transportation cost increase and general building damage cases decrease compared to the baseline level, which indicates that the income losses stemming from these two disaster disruptions/damages categories are born disproportionately by middle- and higher-income groups. Since the impacts of general building damages account for over 90% of the total impacts in the LA Metro Region in the simulated seismic event, the combined simulation of all three types of disruptions/damages also yield lower Gini coefficients than in the baseline. This can be explained by the fact that a higher proportion of capital-related income is earned by higher-income groups. Therefore, these income groups are expected to experience a higher proportion of income losses from property damage.

1. Introduction

Serving as critical portals of a nation's supply-chain, seaports and their associated inland transportation infrastructure are especially vulnerable to major disruptions from a variety of causes. The economic impacts of these disasters can extend well beyond the on-site operations at the port complex, through supply-chain curtailments and/or delays of delivering imports and exports to their destinations.

Assessment of transportation system vulnerability and resilience has gained increasing attention, especially after incidents of port closures and transportation network downtimes following major natural disasters in recent years (such as the major impacts of Superstorm Sandy to Port of New York/New Jersey, Hurricane Irma to Ports of Jacksonville and Miami, and Hurricane Harvey to Port of Houston). Many studies have estimated the direct and indirect impacts of transportation network disruptions in general and port disruptions in particular, and found them to be sizeable (Cho et al., 2001; Tsuchiya et al., 2007; Gordon et al., 2004; Jung et al., 2009; Park et al., 2008; Pant et al., 2011; Rose and Wei, 2013; Xie et al., 2014; Zhang and Lam, 2015; Rose et al., 2016; Rose et al., 2018).

However, most of the economic impact analysis methods and models introduced in the existing literature fail to incorporate the spatially distributed and networked nature of transportation infrastructures. The focus is usually on a single infrastructure component (airport, seaport, bridge, etc.), and thereby omits the interdependency effects in today's networked transportation systems, such as the exacerbation caused by cascading failures. Therefore, to achieve a comprehensive and realistic understanding of the economic impacts caused by the hazard induced disturbances in seaports, the spatial distribution and the networked nature of transportation systems and their post-event degradation has to be taken into account, and realistic and locally relevant hazard scenarios must be incorporated into the economic impact analyses. Furthermore, disasters and their impacts on critical infrastructure do not affect all people in a region equally. Studies have shown that the poor are typically affected proportionally more in relation to their personal incomes than are those in middle and upper-income brackets (Mileti, 1999). Unfortunately, very few studies have analyzed these income distribution impacts (Masozera et al., 2007; Shaughnessy et al., 2010). Moreover, no studies to date have examined the income distribution impacts of more than a select few resilience tactics, which have the ability to reduce regional business interruption losses.

To estimate the aggregate and distributional economic consequences of disasters, we have developed a synergetic approach linking a regional transportation model and a multi-regional computable general equilibrium model (the TERM Model). The integrated model is also capable of analyzing the effects of port and transportation resilience -- ways to reduce the impacts of disruptions to imports and exports through such tactics as input substitutions, use of inventories, conservation, rescheduling of economic activities. Moreover, we constructed and integrated a multi-sector income distribution matrix (MSIDM) into the modeling framework to analyze the impacts of port and transportation network disruption and the effectiveness of resilience tactics across socioeconomic income groups. The integrated model is applied to a previously simulated earthquake scenario that affects commodity flows at the Port of Los Angeles and Port of Long Beach and their associated inland highway transportation network.

The report is divided into eight sections. The background of the study is presented in Section 2, which summarizes the research gaps in applying system-based analysis of transportation system resilience from both the transportation system analysis and economic impact analysis perspectives. In Section 3, we first provide some basic considerations of economic resilience. We then discuss economic resilience tactics that are applicable to transportation system disruptions. In Section 4, we introduce the individual modules of the integrated transportation-socioeconomic impact analysis model we developed. The disaster scenario, which is used as a case study, to illustrate the working of the integrated transportation-socioeconomic model is presented in Section 5. We also introduce the methods to estimate the direct impacts of the simulated disaster scenario in this Section. The results of the direct impacts are presented in Section 6. The economy-wide aggregate impacts and the distributional impacts of the disaster scenario is presented in Section 7. Economic and distributional impacts with and without the consideration of the various resilience tactics are analyzed and evaluated. Section 8 provides a conclusion of the study.

2. Background

2.1. Vulnerability and Resilience of Transportation Systems

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" (risk/vulnerability/consequences) (Kaplan and Garrick, 1981)— has long been the focus. To that end, there is a substantial literature on network vulnerability. Vulnerability for transportation networks is the susceptibility to incidents that can result in considerable reductions in network serviceability (Berdica 2002). Resilience is defined in its broadest sense as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (lessening the abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance) (Bruneau et al., 2003). It offers a broader perspective that highlights how the anticipatory ability of vulnerability analysis can interact with the monitoring (*knowing what to look for*), responding (*knowing what to do*) and learning (*knowing what has happened to be better prepared for the future*) abilities (Hollnagel 2011) in order to contribute to a more resilient system (Mattson and Jenelius, 2015).

Multiple reviews on transportation disruptions (Mattson and Jenelius, 2015; Faturechi and Miller-Hooks, 2014; Khademi et al., 2015) 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, we believe that the resilience perspective offers an opportunity in achieving actionable insights.

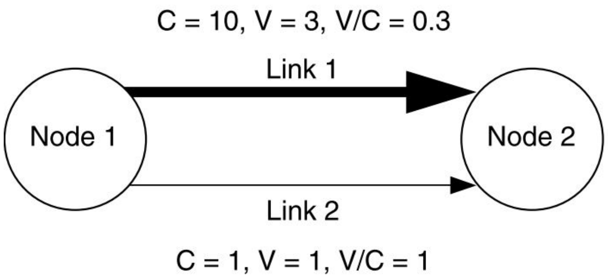
2.2. Towards System-Based Resilience Assessment

Studies on disruption of transportation systems are generally grouped into two main methodological categories: topological (graph theory-based) and system-based approaches (Mattson and Jenelius, 2015). 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 (Koc et al., 2019a). 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 (i.e., maximum 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.

In the context of transportation system disruptions stemming from the hazard-induced degradation of network components, 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 (1997), 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 (2004), 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. (2006) criticize conventional infrastructure management practices based on local Level-of-Service (LOS) measures (e.g., Volume/Capacity ratio) calculated at the link level. We argue local measures are misleading in determining areas of improvement in the network and illustrate the problem with a simple example. In the simple example illustrated with Figure 1, 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. (2006). 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 partial link closures as opposed to binary treatment of failures Sullivan et al. (2010) , designing importance measures that are feasible in the case of non-connected networks or focusing on changes in accessibility to investigate vulnerability (Taylor et al., 2006; Chen et al., 2007).

Figure 1. Example Illustrating Critical Links using V/C Ratios



Source: Scott et al. (2006)

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 (Cetiner et al., 2019). Some researchers followed yet another direction of research focusing on evaluating the vulnerability for specific regions and hazards (Bono and Gutierrez, 2011). 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 (Wei et al., 2018a). To set the stage for the multi-disciplinary and synergetic model presented in this study, research gaps identified by the authors are presented with respect to 2 perspectives: (1) transportation systems analysis, (2) socioeconomic impact analysis. Table 1 summarizes these gaps.

Table 1: Shortcomings in System-based Analyses of Transportation Disruptions.

Transportation System Analysis	**Economic Impact Analysis**
▪ Lack of holistic and granular network modeling representing actual inventory	▪ Predominantly focus on individual components
▪ Post disaster travel behavior treated as a mystery	▪ Commonly used Input-Output (I-O) models have well known limitations: linear, rigid response, lack behavioral content
▪ Abundance of work in single link failures and/or a single mode of transportation. Limited for spatially distributed impacts and multiple modes	▪ Lack of explicit network modeling and formal hazard considerations
▪ Lack of attention to transportation equity related consequences and environmental impacts	▪ Lack of attention to disparities across income groups or impacts on racial/ethnic minorities

2.3. Shortcomings in System-Based Analyses of Transportation Disruptions: 2 Perspectives

Before providing the perspectives on shortcomings in transportation systems analysis and economic impact analysis, 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, 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 many studies have resorted to what-if assumptions to determine physical damages and component failures. Khademi et al. (2015) find in their review that many studies look at failures without considering 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 (Cetiner et al., 2019). In this project, seismic hazard results were adopted from authors' concurrent efforts with collaborators in UCLA's Taciroglu Research Group. Detailed discussions on how these are obtained can be found in (Koc et al., 2020). Below, we discuss the shortcomings from transportation and economic perspectives.

2.3.1. 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) (Koc et al., 2019b). 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 (Koc et al., 2019). Nagae et al. (2012) points out suggestions by Asakura on network models to be utilized in vulnerability research. According to Asakura (2007), 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.

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. (Chen et al., 2007) even if the predictions depend on simple evaluations of existing demand functions or sensitivity analyses linked to what-if type assumptions. 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. Nicholson (2007) 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. (2015) also identify the isolation of the pre-disaster phase by many studies. Mattsson and Jenelius (2015) 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.

2.3.2. 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 (Wei et al., 2018b). 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 associated with tabulating property damage or lost business revenue. These articles do not take inter-industry supply-chain effects or inter-regional economic diffusion effects into consideration. Among the articles with formal economic impact estimation methodologies, Input-Output (I-O) modeling in general (including Interoperability I-O modeling) is a widely used approach (Okuyama and Santos, 2014: Santos, 2006). I-O Is a model of all purchases and sales between sectors of an economy, based on the technological relationships of production (Rose, 2004a). In addition, there are several examples of the state-of-the-art approach in this area, such as Computable General Equilibrium (CGE) and Spatial CGE models (SCGE) (Rose, 2005). CGE is a multi-market simulation model based on simultaneous optimizing behavior of individual consumers and firms, subject to economic account balances and resource constraints (Rose, 2004a). 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. 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 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 of these studies estimated the indirect economic losses based on the direct losses (i.e., decreased proportion of initial production or demand), which were hypothetical or simply set according to historical records.

3. Economic Resilience to Transportation Systems Disruptions: Ports and Hinterland Road Networks

3.1. Basic Considerations of Economic Resilience

In the past few years, many analyses of the impacts of disasters in the U.S. have highlighted the "resilience" of the economy (see, e.g., Boettke et al., 2007; Chernick, 2005; Flynn, 2008; Rose et al., 2009). Resilience is often used to explain why regional or national economies do not decline as much as might be expected after disasters, or why they recover more quickly than predicted. The concept has received increasing emphasis for more than a decade, with progress on its definition stemming from the work of Tierney (1997), Bruneau et al. (2003), Chang and Shinozuka (2004), and Rose (2004a, 2017). Various disciplines and definitions seem to be evenly split between those that define resilience broadly to include attributes that contribute to pre-event disaster resistance, and those who prefer to reserve the terms for actions undertaken after a disaster begins that are intended to reduce losses. In this study, we exclude pre-event actions that fall into the broad category of mitigation, though we do include pre-event actions that enhance resilience capacities that are implemented after the event as discussed below.

Although there are many definitions of resilience, Rose (2009, 2017), Cutter (2017) and others have found more commonalities than differences. We offer the following general definitions of resilience, which capture the essence of the concept, and then follow them with definitions that capture the essence of economic considerations. Following Rose (2004b, 2017), we distinguish two major categories:

- In general, Static Resilience refers to the ability of the system to maintain a high level of functioning when shocked (Holling, 1973). *Static Economic Resilience* is the efficient use of remaining resources at a given point in time. It refers to the core economic concept of coping with resource scarcity, which is exacerbated under disaster conditions.

- In general, Dynamic Resilience refers to the ability and speed of the system to recover (Pimm, 1984). *Dynamic Economic Resilience* is the efficient use of resources over time for investment in repair and reconstruction. Investment is a time-related phenomenon—the act of setting aside resources that could potentially be used for current consumption in order to re-establish productivity in the future (Rose and Dormady, 2018). Static Economic Resilience does not completely restore damaged capacity and is therefore not likely to lead to complete recovery.

The analysis in this study focuses on *static* economic resilience on both the customer-side and supplier-side.

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Rose, 2004b Tierney, 2007; Cutter, 2016). Inherent resilience refers to resilience capacity that is either already built into the system or that can be incorporated in advance of the disruption by enhancing resilience capacity though "pre-positioning". Examples include the ship rerouting, other transport mode shifts, and geographic production shifts, all stimulated by the workings of the market system in providing price signals for decision about redirecting scarce resources. Adaptive resilience is exemplified by undertaking conservation that was not previously thought possible, changing technology, or devising new government post-disaster assistance programs. The focus of economic resilience is not on property damage, which has already taken place at the onset of the disruption, but rather the reduction in the loss of the *flow of goods and services* emanating from the damage to or cessation of operation of the port's *capital stock*. The former is often measured in terms of the reduction in the level of production at the micro level or by GDP at the macro level, and is typically referred to as business interruption, or BI. Note that BI just begins at the point when the disaster strikes, but continues until the system has recovered (Rose, 2017). [1]

In contrast to property damage, which is a "stock" concept measured at a given point, business interruption (BI) refers to the "flow" of goods and services emanating from the stock and is usually measured in terms of loss of gross domestic product (GDP). It begins at the point of the disruption and continues until the port has recovered. Economic resilience is essentially a way of reducing BI and is measured in terms of GDP as well.

Economic resilience can be analyzed at three levels:

- Microeconomic (individual business, household, or government)
- Mesoeconomic (individual industry or market)
- Macroeconomic (combination of all economic entities, including their interactions)

At the microeconomic level, on the business supplier side, static economic resilience includes redundant systems, improved delivery logistics, and planning exercises. Several options also exist on the business customer side. Broadening the supply chain (see, e.g., Sheffi, 2005) by expanding the range of suppliers in place or on a contingency basis is an increasingly popular option. Other resilience tactics include conservation, input and import substitution, use of inventories and excess capacity, cross-training workers, relocation, and production recapture (working overtime and extra shifts when functionality is restored to make up lost production). At the mesoeconomic level, resilience can bolster an industry or market and include, for instance, industry pooling of resources and information and innovative pricing mechanisms. What is often less appreciated is the inherent resilience of market prices that act as the "invisible hand" to guide resources to their best allocation in the aftermath of a disaster (see, e.g., Horwich, 1995). At the macroeconomic level, resilience is very much influenced by interdependencies between sectors. Consequently, macroeconomic resilience is not only a function of resilience measures implemented by single businesses but is also determined by the actions taken by all individual companies and markets, including their interaction

In order to evaluate the effects of resilience, the next step is to translate these definitions into something that can be measured. Following Rose (2004b, 2017), for static resilience, the metric is the amount of BI prevented by the implementation of a given resilience tactic or set of tactics comprising a resilience strategy divided by the maximum potential BI from the disaster if the tactic were not

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[1] The Port makes decisions on such tactics as the use of excess capacity and ship-rerouting, and the various direct and indirect customers make decisions about how to cope with the supply shortages under their own roof. There is a minimal role for government in this decision process, in part it would interfere with day-to-day operations of businesses. Governments rarely provide financial assistance to port customers, and this only serves as compensation for decisions that businesses are inclined to make on their own to minimize the negative impact on their operations. If the government is more likely to compensate firms for some resilience tactics over others, businesses still need to know the relative effectiveness of those tactics in gauging their response.

implemented. Several studies have measured resilience using this and related metrics (see, Rose et al. 2009; Rose and Wei, 2013; Xie et al., 2014).

A basic operational measure of static economic resilience is the extent to which the reduction in BI deviates from the likely maximum potential reduction given an external shock. The notational form for evaluating the static economic resilience as suggested by Rose (2004a; 2009b) can be expressed as:

$$SER = \frac{\%\Delta Y^m - \%\Delta Y}{\%\Delta Y^m} \tag{3.1}$$

where

SER represents Static Economic Resilience
$\%\Delta Y^m$ is the maximum percent change in economic output
$\%\Delta Y$ is the actual percent change in economic output

In essence *SER* is the percentage avoided of the maximum economic disruption that a particular shock could bring about. A major measurement issue involves what should be used as the maximum potential disruption. For ordinary disasters, a good starting point is a linear, or proportional, relationship between an input supply shortage and the direct disruption to the firm or industry. Note that while a linear reference point may appear to be arbitrary or a default choice, it does have an underlying rationale. A linear relationship connotes rigidity, the opposite of the "flexibility" connotation of static resilience defined in this report. In contrast, resilience represents the introduction of non-linearities. An analogous definition pertains to resilience taking into account indirect or macroeconomic effects.

3.2. Economic Resilience Tactics Applied to Transportation System Disruption

Port resilience is a special case of economic resilience (Rose and Wei, 2013). In the context of a port shutdown or disruption, *static* economic resilience relates to the operation of the port and the activities of both its direct customers (importers and exporters) and businesses upstream and downstream along the supply chain of these direct customers. It refers to how ports and businesses can utilize remaining resources effectively to maintain functioning to the extent that they can. Supplier-side resilience is concerned with delivering outputs to customers, and, in the context of a port disruption, it refers to maintaining functionality at the port. (The various resilience tactics ports undertake to accelerate the speed of recovery of port operations through investment in restoring port capacity come under the heading of *dynamic* economic resilience, and are not analyzed here.) On the customer-side, businesses that are affected by the import or export disruptions could initiate a broad range of coping activities. These actions are taken not only by importers and exporters, but also by others that are indirectly affected by the port disruptions throughout the economy-wide supply chain.

Expanding on Rose and Wei (2013), Wei et al. (2016), and Wei et al. (2020), we define the various supplier-side and customer-side resilience options relating to ports and their hinterland transportation system disruptions in Table 2.

Table 2. Summary of Resilience Tactics Relating to Port and Highway Transportation Disruptions

Supplier-Side Resilience Options	**Customer-Side Resilience Options**
Excess capacity. Utilization of unused capacity at undamaged terminals to unload/load cargo originally handled in other terminals that experience facility downtime.	*Use of inventories*. Stockpiling critical inputs for the production of goods and services by firms (the cost of inventories is not the actual value of the goods themselves, but simply the carrying costs).
Cargo prioritization. Altering schedules for unloading or loading based on the characteristics or value of the cargo (e.g., giving higher priority to perishable items, critical and emergency supplies, high value commodities).	*Conservation*. Finding ways to utilize less of disrupted imported goods in production processes, as well as conserving critical inputs whose production is curtailed indirectly.
Ship re-routing. Sending ships to other ports; require an assessment of alternative locations, ship/cargo type, transportation costs, and extent to which some cargo can eventually be re-routed to the disrupted port area through land surface or sub-surface (pipeline) transportation.	*Input substitution*. Utilizing similar goods in the production process to those whose production has been disrupted (again both directly and indirectly).
Export diversion for import use. Sequestering goods that were intended for export to substitute for lack of availability of imports or domestically-produced goods that require imported inputs (need to analyze at a very disaggregated commodity level).	*Import substitution*. Bringing in goods and services in short supply from outside the region through transportation means other than water transportation.
Effective management. Improvements in decision-making and expertise that enhance functionality (e.g., establishing port-level emergency-management plans to share information and facilitate communications; effectively allocating manpower and other resources to expedite debris removal, repair, and reconstruction).[2]	*Production relocation.* Shifting production to branch plants or losing production opportunities to competitors in other locations.
Production recapture (Rescheduling). Working extra shifts or over-time to clear up backlog of vessels after resumption of port operation (only viable for short-run disruptions, for which most ships will wait for the re-open of the port, rather than re-rout to other ports).	*Production recapture (Rescheduling)*. Making up lost production by working extra shifts or over time after the port re-opens and the supply of critical inputs resumes. This is a viable option for short-run disruptions, where customers are less likely to have cancelled orders.
Effective road infrastructure asset management. Improvements in decision-making and expertise that enhance functionality and recovery (e.g., optimizing restoration by identifying critical corridors, effectively allocating manpower and other resources to expedite repair and reconstruction, re-routing and rescheduling heavy duty traffic away from peak times)	
Effective travel demand management. Establishing measures to decrease travel demand during recovery (e.g, incentivize or enforce telecommuting for certain industries to decrease travel demand, improvements in communicating traffic conditions to general public., etc.)	

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[2] Such effective management measures can be potentially built on existing data-driven commodity throughput portal and port community communication systems. See Appendix A for a summary of the Port Optimizer that is being deployed in POLA/POLB.

4. Integrated Transportation-Socioeconomic Impact Analysis System

4.1. Analysis of the Transportation System Disruption

4.1.1. Transportation Networks and Concept of Resilience

In the investigation of system resilience as an emergent capability for the networked transportation system, the following analytical resilience definition of Frangopol and Bocchini (2011) is adopted here:

$$R = \frac{1}{h}\int_{t}^{t+h} Q(t)dt \qquad (4.1)$$

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 (2011), 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 (2011) where all the bridges are out-of-service is also left out as it is not a realistic one for metropolis-scale systems.

$$Q(t) = 1 - \frac{|\Gamma(t) - \Gamma(0)|}{\Gamma(0)}; \quad Q(t)\epsilon[0,1] \subset R \qquad (4.2)$$

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.[3]

Being centered around a detailed, high-resolution model of the transportation system, the systems analysis approach used in this study (See Figure 2) allows for the quantification of virtually all such indicators. *Γi(t)* is typically calculated as a sum over all links (denoted as *j* in Equation 4.3) in the network at time t for indicator i (i denotes any indicator such as *VMT* (Vehicle-Miles-Traveled), *VHT* (Vehicle-Hours-Traveled), or *Delay* (Vehicle-Hours-Delayed)) (See Equation 4.3). Other less visited indicators such as average speed can be calculated as a mean over all the links.

$$\Gamma_i(t) = \sum_j \text{FunctionalityIndicator}_{ij}(t)\,; \quad \Gamma_i(t)\epsilon R^+ \qquad (4.3)$$

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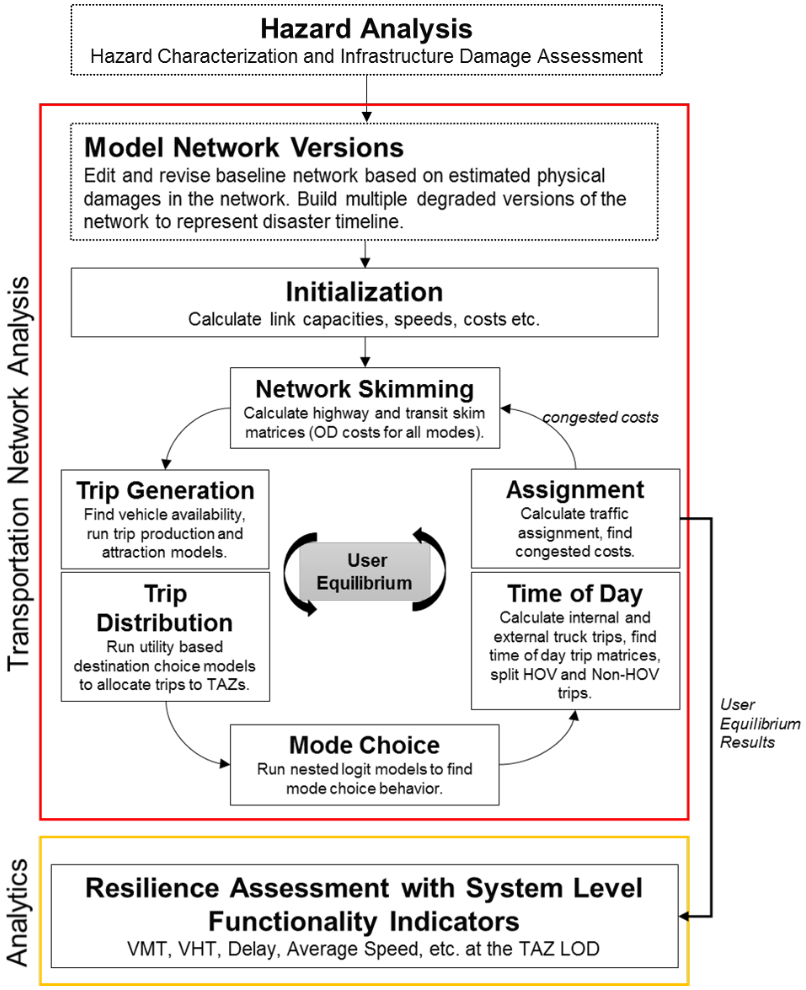
[3] This is essentially the same metric expressed in equation 3.1, but is scaled and bounded.

4.1.2. Investigation of Transportation Resilience with the SCAG Regional Travel Demand Model

Figure 2. Investigation of Transportation Resilience with the SCAG RTDM



Based on the results of the hazard characterization and damage assessment procedures described in Koc et al. (2020), the analysis of the transportation network disruption is realized with a metropolis scale 4-step travel demand model. Figure 2 shows the analytical framework. Specifically, functionalities of damaged system components (functionality relates to damage state) 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 (origin-destination) 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 complete 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. We implement this methodology, for every network topology (pre-disaster baseline and post-disaster degraded versions). The methodology, however, may differ based on the modeling of 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.

The transportation system analysis component of the project illustrated with the workflow in Figure 2 is implemented with the regional travel demand model (RTDM) developed by the Southern California Association of Governments (SCAG), as part of their regional transportation plan (SCAG, 2019). The peer-reviewed model is developed and operated on TransCAD, and it is validated with a number of independent sources of travel data including such as auto and truck traffic counts, transit boarding counts, Vehicle Miles of Travel (VMT) from Highway Performance Monitoring System (HPMS), speed data from Freeway Performance Measurement System (PeMS), and other travel survey data. 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 Figure 2 for network 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), calibration with respect to the California Household Travel Surveys and other data sources, 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. The model is peer-reviewed and validated against actual traffic counts in the region. To our knowledge, it has not been utilized for resilience assessments.[4].

The most recent version of the SCAG RTDM model was used by the research team with year 2016 socioeconomic data. The model and the underlying network are highly granular (See Figure 3) and accommodates a holistic transportation network enabling a wide range of analyses including

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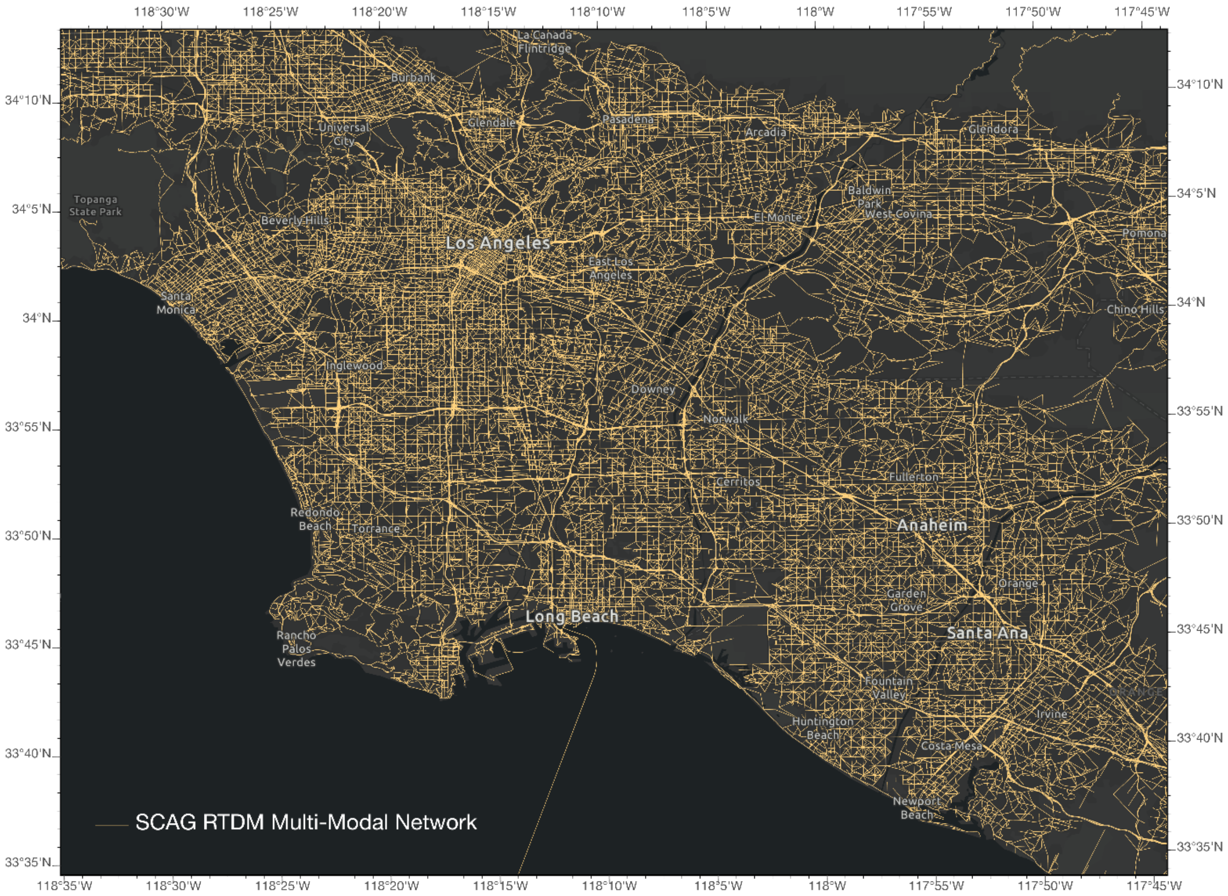
[4] For detailed discussions regarding the data sources and the modeling efforts related to SCAG RTDM, readers are referred to the model validation report online (SCAG, 2019)

investigations of expansion projects, highway pricing strategies, introduction of new types of transportation services, etc. In accordance with the framework demonstrated with Figure 2, the project team used the model to determine the pre-disaster condition of the multi-modal transportation system (baseline) as well as its condition in post-disaster settings (e.g., day 30 after a scenario earthquake).

Figure 3. Network Model Resolution in SCAG RTDM



Details regarding hazard analysis are omitted here due to the focus on the transportation – economics modeling interface. However, it is essential to note that hazard analysis outputs include restoration (recovery) timelines for damaged bridges given a specific earthquake scenario. In other words, bridge functionalities are—roughly—known throughout the disaster timeline. These results from hazard assessment are integrated into the transportation model by manipulating the network topology underlying the transportation model to represent the degradation. For example, if a bridge is damaged and cannot service traffic until reconstruction and recovery activities happen, the links and public transit routes going through the bridge are modeled to be closed in the transportation model. These modifications decrease the network supply and disrupt the business-as-usual flows in the study region. Through these modifications, the objective is to capture snapshots of the transportation disruption and the recovery in terms of network level functionality indicators such as VHT, VMT, delay, average speed etc. while ensuring the granularity of such results at the TAZ level of detail.

In summary, the transportation system analysis facet of this project 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. As mentioned in earlier sections, this underlines the ability of the analytical framework to bridge a significant gap between transportation resilience research and policy-making.

4.2. The TERM Multi-Sector CGE Model

In this study, we use a multi-regional computable general equilibrium (CGE) model – TERM– to analyze the total economic impacts of the seismic hazard scenario and the effectiveness of economic resilience. CGE models are the state-of-the-art model among all economy-wide modeling approaches used to study economic consequences of disaster. Essentially, CGE models the economy as a set of integrated supply chains in relation to behavioral responses of businesses and consumers to market price signals and resource constraints. The CGE formulation incorporates many of the best features of other popular model forms, but without many of their limitations. For example, CGE models retain the major strengths of input-output models (full accounting of all inputs, multi-sector detail, and ability to capture interdependencies), but overcome the limitations of linearity, lack of behavioral content, lack of input and import substitution possibilities, and difficulty of incorporating resource constraints. This modeling approach has been shown to represent an excellent framework for analyzing natural and man-made hazard impacts and policy responses, including disruptions of transportation infrastructure (Chen and Rose, 2018; Rose et al., 2017; Avetisyan et al., 2015). We also constructed a Multi-sector Income Distribution Matrix (presented in detail in Task 1 Report) to analyze the income distributional impacts of the disaster scenario that causes disruptions of port operations and disturbance of the inland freight transportation network.

TERM is a "bottom-up" model that treats each region as a separate economy.[5] The model was custom built by the research team at the Centre of Policy Studies at Victoria University in Australia and has undergone several refinements (Horridge et al., 2005; Wittwer, 2012). The TERM modeling framework was adapted to the U.S. on the basis of regional I-O data for the Year 2010, supplemented by various elasticities gleaned from the literature.[6] A key feature of TERM, in comparison to other CGE models, is

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[5] A “bottom-up” approach means that national results are aggregated based on regional economic outputs, which are simulated initially in a multi-regional CGE model. Unlike the “top-down” approach to regionalization, typically one of proportioning national values to regional levels on the basis of regional control totals, such as sectoral gross output, as a proportion of national totals (see, e.g., Dixon et al., 2007), a multi-regional CGE model developed through a “bottom-up” approach consists of multiple independent regional accounts and interregional trade involving various commodities and factor flows. Since price and quantities in different regional accounts are determined endogenously in the model by supply and demand both interregionally and intraregionally, the multi-regional model is able to measure distinct regional impacts and associated regional spatial reallocations caused by a policy simulation.

[6] The Armington and factor input elasticities of substitution in the TERM Model have accumulated in the work of Peter Dixon and his collaborators beginning with the ORANI Model (Dixon, 1982) up through more recent work on the US Multi-Regional Dynamic CGE Model (USAGE) (Dixon et al., 2017). The Armington elasticities take on values from 2.0 to 10.0 and the input elasticities are typically around 0.5, which falls in between typical short-run and long-run values. They are already more restrictive (have lower numerical values) than most other CGE models

its ability to handle a greater number of regions and sectors. The high degree of regional detail makes TERM a useful tool for examining the region-specific impacts of shocks (especially supply-side shocks). In addition, TERM contains a detailed treatment of transportation costs and is well-suited to simulating the effects due to damages of transportation infrastructures. The TERM Model has been used in many studies that analyze trade-related issues and some analyses of disaster. The TERM Model used in this study is static, which simulates the impacts of port and transportation network disruptions on the economy on an annual basis.

The modeling structure of TERM is similar to that of other CGE models (Horridge, 2012). Producers in each region are assumed to minimize production costs subject to a combination of intermediate and primary factor inputs, which are characterized by a Constant Elasticity of Substitution (CES) nesting structures. As illustrated in Appendix B, at the top nest level, output is produced by combining a composite of primary factors with a composite of intermediate inputs. The primary factor aggregate is a CES composite of capital, land, and labor—the latter being itself a CES composite of labor by skill type. The aggregate intermediate input is also a CES composite of composite commodities, which are in turn CES composites of commodities from various sources. A representative household in each region maximizes utility through purchases of optimal bundles of goods in accordance with its preferences and budget constraint.

The TERM database used for our study consists of 4 regions and 97 economic sectors. The regions include: LA Metro Region (including Los Angeles, Orange, and Riverside Counties), SF Metro Region (including Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma counties), and the Rest of California, and the Rest of the U.S.[7] Simulations in the TERM Model was conducted based on a short-run closure rule, under which wage was treated exogenously, whereas employment is adjusted endogenously.

4.3. Construction of the Multi-Sector Income Distribution Matrix of California

In order to evaluate the impacts of port and transportation network disruptions and the effectiveness of resilience tactics not only across economic sectors, but also across socioeconomic groups (specifically income groups), a Multi-Sector Income Distribution Matrix (MSIDM) for the state of California is constructed. Figure 4 presents a schematic depiction of a MSIDM. The matrix provides the earnings profile according to nine income brackets for each producing sector in the economy, i.e., what proportion of the personal income (including both labor income and capital income) paid out by each sector accrues to each income bracket (Rose et al., 1988; Li et al., 1999).

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employing CES production functions, and much more restrictive than those using Cobb-Douglas production functions, where the elasticity of substitution has to be equal to 1.0. Overall, the estimation of the elasticities in the TERM Model is relatively weak in comparison to a CGE model whose elasticities were estimated from a consistent set of time series data, though we point out that few such models exist.

[7] A major focus of our study is the methodological contribution, such that our 4-region analysis is capable of providing it and in a generalizable manner. Our 4 regions cover the entire US and thus the analysis can adequately capture the spatial substitution effects among the sub-regions of California and between these regions and Rest of US.

Figure 4. Schematic Depiction of a Multi-Sector Income Distribution Matrix

Income Bracket / Industry	<5k	5-12.5k	12.5-17.5k	17.5-25k	25-32.5k	32.5-42.5k	42.5-55k	55-77.5k	77.5-130k	>130k
Agriculture	x	x	x	x	x	x	x	x	x	x
Construction	x	x	x	x	x	x	x	x	x	x
Manufacturing	x	x	x	x	x	x	x	x	x	x
Transportation	x	x	x	x	x	x	x	x	x	x
Service	x	x	x	x	x	x	x	x	x	x
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4.3.1. Overview of the Major Components of Personal Income Accounts

In 2018, the total personal income in California was more than $2.4 trillion (BEA, 2019). Table 3 presents the major components of the personal income accounts for the state. The first major component is Wages and Salaries, which include total remuneration of employees. The total Employee Compensations, which were $1.35 trillion in 2018, are the sum of Wages and Salaries and Employer Contributions for Employee Pension and Insurance Funds. The Employer Contribution for Government Social Insurance is counted in Earnings by Place of Work, but not in Net Earnings by Place of Residence and Personal Income (BEA, 2017). For sole proprietorships, partnerships, and tax-exempt cooperatives, the current-production income is shown in the Proprietors' Income rows (which include $12.3 billion of Farm Proprietors' Income and $237.3 billion Non-farm Proprietors' Income).

The next major component of the personal income accounts is capital income, which include dividends (payments from corporations to stockholders), interest payments (such as savings interest, bond interest payments, etc.), and rental income (income from rental properties), which amounted to $538.3 billion in California in 2018.

The final major component of the personal income accounts is Personal Current Transfer Receipts. These mainly include payments from government welfare and benefit programs, such as social security benefits, medical benefits, veteran's benefits, and unemployment insurance benefits. The total amount of Personal Current Transfer Receipts in California in 2018 was $341.2 billion.

The BEA Personal Income accounts for California presented in Table 3 will be used as control totals when we construct the individual income matrices in the following sections.

Table 3. California Personal Income by Major Components for 2018 (millions of dollars)

Earnings by place of work	1,778,305
Wages and salaries	1,250,685
Supplements to wages and salaries	277,948
Employer contributions for employee pension and insurance funds	196,887
Employer contributions for government social insurance	81,061
Proprietors' income	249,672
Farm proprietors' income	12,348
Nonfarm proprietors' income	237,324
Less: Contributions for government social insurance	180,175
Plus: Adjustment for residence	-1,948
Plus: Dividends, interest, and rent	538,325
Plus: Personal current transfer receipts	341,220
Personal income	**2,475,727**

Source: BEA (2019).

4.3.2. Household Income Brackets

In this study, we adopt the nine household income brackets that are used in IMPLAN (the largest provider of regional input-output and social accounting data in the U.S.). As discussed in detail below, we will use IMPLAN as the main data source to distribute proprietors' income, dividends, other property income, and transfers across sectors and income brackets. Table 4 presents the nine IMPLAN household income brackets and the number of households in each bracket.

4.3.3. Employee Compensation

To construct the income distribution matrix for wages and salaries, we first collected data from the BLS Occupational Employment Statistics (OES) (BLS, 2019a). The two main matrices we use are the Occupation-Industry Employment matrix and the Occupation-Industry Wage matrix. The industries are disaggregated at 4-digit NAICS level and the occupation categories follow the 6-digit Standard Occupational Classification. For each occupation type of a given industry, BLS OES data report not only the annual average (mean) wages, but also wage rate in percentiles (10, 25, 50, 75, 90). One limitation of this data set was that the minimum and maximum wage percentiles are 10 and 90, respectively, and hence it does not readily provide information on the wage rate for the highest and lowest earners. In order to deal with this limitation, we estimated annual wage rates for an extended set of percentiles (1, 5, 20, 40, 60, 80, 95, 99) using linear interpolations following the methodology developed by Rose et al. (2012) and Prager (2013).

Table 4. IMPLAN Household Income Brackets

Household Income Bracket	No. of Households	% of Households
<15k	1,442,921	10.9%
15-30k	1,836,015	13.9%
30-40k	1,142,466	8.6%
40-50k	1,040,681	7.9%
50-70k	1,811,813	13.7%
70-100k	1,992,294	15.1%
100-150k	1,978,213	15.0%
150-200k	922,618	7.0%
200k+	1,050,542	7.9%
Total	13,217,563	100.0%

Source: IMPLAN (2018).

The wage data for the OES survey are straight-time, gross pay, and exclude any premium pay (BLS, 2019a). In addition, any other employee benefits and compensations are not included. In order to calculate the total employee compensation, we collect BLS data on Employer Costs for Employee Compensation (BLS, 2019b). Table 5 presents the percentages of total compensation between Wages and Salaries and various types of employee benefits by major occupation category at the national level. Table 6 presents similar percentages by major industry group. We first calculated the Total Compensation to Wages and Salaries ratio by occupation group using data in Table 5 to scale up wage data to employee compensations. For example, the weighted average ratio for all occupations is 1.39, which is calculated by subtracting the percentage of employer contribution to government social insurance (4.5%) from the 100% and then divided it by the percentage of wages and salaries (68.6%) in total compensation. We then adjusted for the variations of this ratio across industry sectors by using the data presented in Table 6. For example, the Total Compensation to Wages and Salaries ratio is relatively smaller for the Leisure and Hospitality sector compared to the Utilities sector.

After we calculated the annual employee compensation by sector and occupation for each percentile (1, 5, 20, 40, 60, 80, 95, or 99), we multiply it by the number of employees in each percentile interval of this occupation in this sector to obtain the total employee compensations by percentile. Next, the total employee compensations by percentile and sector are allocated to the relevant household income brackets. The OES sectors are also mapped to the TERM CGE model sectors (see the TERM sectoring scheme in Appendix B). Finally, we used the estimate of Total Employee Compensations in California in 2018, which was $1.346 trillion, as the control total to re-balance the entire Employee Compensation matrix we constructed. The final matrix is presented in Appendix Table C1.

Table 5. Percent of Total Compensation by Occupational Group

Occupation Group	Total Compensation	Wages & Salaries Total	Paid Leave	Supplemental Pay	Insurance	Retirement & Savings	Legally Required Benefits
Management, professional, and related	100	68.4	8.4	2.7	8	6.2	6.2
Management, business, and financial	100	68.4	9.3	3.8	6.9	5.3	6.3
Professional and related	100	68.4	7.9	2.2	8.6	6.7	6.2
Teachers	100	68.3	5.2	0.4	10	10.9	5.2
Primary, secondary, & special education school teachers	100	66.6	4.7	0.3	11	12.6	4.8
Registered nurses	100	65.6	9.4	3.6	9.3	5.4	6.6
Sales and office	100	70.1	6.7	2.5	9.5	3.8	7.4
Sales and related	100	75.4	5.7	2.5	6.1	2.5	7.7
Office and administrative support	100	67.2	7.3	2.5	11.3	4.5	7.2
Service	100	71.2	5.2	2.1	8.4	4.4	8.7
Natural resources, construction, & Maintenance	100	67	5.4	3.3	9	5.9	9.5
Construction, extraction, farming, fishing, & forestry	100	66.3	4.2	3.2	8.9	7	10.4
Installation, maintenance, and repair	100	67.7	6.6	3.3	9.1	4.7	8.6
Production, transportation, and material moving	100	65.7	6	4	10.5	4.7	9.1
Production	100	66.3	6.1	4.8	10.7	3.5	8.7
Transportation and material moving	100	65.1	5.9	3.3	10.3	5.8	9.5
Total	100	68.6	7.2	2.8	8.7	5.4	7.3

Source: BLS (2019b).

Table 6. Percent of Total Compensation by Industry Group

Industry Group	Total Compensation	Wages & Salaries Total	Paid Leave	Supplemental Pay	Insurance	Retirement & Savings	Legally Required Benefits
All workers, goods-producing industries	100	66.7	6.5	4.3	9.2	4.9	8.4
Construction	100	69.2	4.4	3.1	8	5.3	10
Manufacturing	100	65.5	7.6	4.9	9.9	4.5	7.7
Aircraft manufacturing	100	60.5	8.9	7.1	10	7.1	6.4
All workers, service-providing industries	100	70.8	7.3	3	7.7	3.6	7.6
Trade, transportation, and utilities	100	70.2	6.3	2.8	8.2	4.2	8.3
Wholesale trade	100	70.7	7.3	3.1	7.7	3.6	7.6
Retail trade	100	75.3	4.8	2.2	6.8	2.3	8.6
Transportation and warehousing	100	64.3	7	3.3	10.4	6.3	8.7
Utilities	100	60.8	8.6	3.6	9.9	10.1	7.1
Information	100	66.3	9	4.5	8.5	5.2	6.5
Financial activities	100	67.3	8.6	5.4	8.5	3.7	6.5
Finance and insurance	100	66.3	9	5.9	8.5	4.1	6.2
Credit intermediation and related activities	100	66.8	9.1	4.8	9.1	3.7	6.5
Insurance carriers and related activities	100	65.6	8.8	5.8	8.9	4.6	6.3
Real estate and rental and leasing	100	71.8	6.8	2.8	8.5	2.2	7.9
Professional and business services	100	71.9	7.9	3.2	6.3	3.3	7.4
Professional and technical services	100	71.7	8.7	3.1	6.4	3.3	6.9
Administrative and waste services	100	75.6	4.9	2.7	6	1.6	9.2
Education and health services	100	70.3	8.3	2.2	8.5	3.6	7.1

Industry Group	Total Compensation	Wages & Salaries Total	Paid Leave	Supplemental Pay	Insurance	Retirement & Savings	Legally Required Benefits
Educational services	100	72.1	7.8	0.5	8	4.8	6.8
Junior colleges, colleges, and universities	100	69.7	9	0.7	8.9	5.3	6.5
Health care and social assistance	100	70	8.3	2.5	8.6	3.4	7.1
Leisure and hospitality	100	78.3	3.3	1.5	5.5	1.5	9.9
Accommodation and food services	100	78.3	3.1	1.5	5.4	1.5	10.1
Other services	100	73	5.9	1.5	7.4	4.3	8
State and Local Government	100	62.5	7.5	1	11.8	11.8	5.5

Source: BLS (2019b).

4.3.4. Proprietors' Income

The distribution of proprietors' income across sectors and income brackets is calculated based on IMPLAN data. Table 7 presents the distribution of proprietors' income among the nine income brackets obtained from IMPLAN. In addition, IMPLAN also provides data on the amount of proprietors' income generated in each sector. We apply the distribution percentages across the nine income brackets in Table 7 to the total proprietors' income for each sector to obtain the distribution of proprietors' income across income brackets for each sector. The underlying assumption is that the proportional distribution of proprietors' income among the income brackets is the same across all sectors. Finally, we used the BEA estimate of total proprietors' income in California in 2018, which was $249.7 billion, as the control total to re-balance the entire proprietors' income matrix we constructed. The final matrix is presented in Appendix Table C2.

Table 7. Distribution of Proprietors' Income among Income Brackets

Household Income Bracket	Proprietors' Income ($M)	Percent Distribution
<15k	0	0.0%
15-30k	2,179	1.2%
30-40k	2,992	1.6%
40-50k	4,179	2.3%
50-70k	9,880	5.3%
70-100k	16,441	8.9%
100-150k	29,035	15.7%
150-200k	24,061	13.0%
200k+	96,691	52.1%
Total	185,458	100.0%

Source: IMPLAN (2018).

4.3.5. Capital Income

IMPLAN also provides data on the distribution of the total Dividend Payments and Other Property Income (which mainly includes interest payments and rent income) across income brackets. Table 8 presents the distributions in both dollar and percentage terms. In addition, IMPLAN also provides data on the amount of Other Property Income by sector. We first calculated the percentage distribution of Other Property Income across sectors, and then apply it to the total amounts of Dividend Payments and Other Property Income in each income bracket to obtain the distribution across sectors for each income bracket. The underlying assumption is that the proportional distribution of Dividend Payments and Other Property Income among the sectors is the same across all income brackets. Finally, we used the BEA estimate of total Dividends, Interest, and Rental Income in California in 2018, which was $538.3 billion, as the control total to re-balance the capital income matrix we constructed. The final matrix is presented in Appendix Table C3.

Table 8. Distribution of Dividend Payments and Other Property Income among Income Brackets

Household Income Bracket	Dividend Payments ($M)	Percent Distribution of Dividend Payments	Other Property Income ($M)	Percent Distribution of Other Property Income
<15k	875.7	0.6%	1,615.1	0.8%
15-30k	2,894.3	2.1%	3,937.3	2.1%
30-40k	3,074.0	2.2%	4,037.3	2.1%
40-50k	3,708.9	2.7%	5,333.1	2.8%
50-70k	8,277.2	6.0%	16,400.0	8.6%
70-100k	11,305.7	8.1%	22,280.4	11.7%
100-150k	18,317.2	13.2%	31,230.9	16.3%
150-200k	14,291.9	10.3%	21,139.3	11.1%
200k+	76,059.8	54.8%	85,132.8	44.5%
Total	138,805	100.0%	191,106	100.0%

Source: IMPLAN (2018).

4.3.6. Personal Transfer Receipts

The final component of the personal income accounts is the personal transfer receipts (including social security benefits, medical benefits, veteran's benefits, and unemployment insurance benefits). IMPLAN provides data on the distribution of federal, state and local government transfer payments to each household income bracket. Table 9 presents the distributions in both dollar and percentage terms. Similar as for the other components of the personal income accounts, we used the BEA estimate of total Personal Current Transfer Receipts in California in 2018, which was $341.2 billion, as the control total to re-balance the transfer income matrix we constructed. The final matrix is presented in Appendix Table C4. For this matrix, there are only numbers in the State & Local Government and Federal Government rows.

Table 9. Distribution of Personal Transfer Receipts among Income Brackets

Household Income Bracket	Personal Transfer Receipts from State & Local Government		Personal Transfer Receipts from Federal Government	
	Value	Percent	Value	Percent
<15k	13,216.5	8.2%	21,823.3	7.5%
15-30k	35,578.6	22.1%	59,075.3	20.3%
30-40k	21,303.7	13.3%	35,784.5	12.3%
40-50k	16,258.4	10.1%	27,693.5	9.5%
50-70k	21,277.3	13.2%	37,249.5	12.8%
70-100k	17,414.2	10.8%	31,633.1	10.9%
100-150k	14,870.9	9.2%	28,822.0	9.9%
150-200k	6,207.5	3.9%	13,075.8	4.5%
200k+	14,644.7	9.1%	35,506.1	12.2%
Total	160,771.9	100.0%	290,663.0	100.0%

Source: IMPLAN (2018).

4.3.7. Total Personal Income Matrix

Finally, we added all the matrices of various personal income components we developed in the previous sections to produce the total personal income matrix. This matrix is presented in Table 10. In Table 11, we calculated the total income coefficient matrix for California by dividing the income value for each bracket in a given sector by the total income for that sector.

Table 10. Multi-sector Income Distribution Matrix for California, 2018

(millions of 2018$)

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
01. Crops	17	158	3,284	4,056	1,648	1,497	1,991	1,606	6,194	20,451
02. Poultry & Eggs	0	3	38	48	23	24	36	29	114	315
03. Livestock	4	35	188	237	191	250	397	319	1,296	2,916
04. Other Livestock	1	3	14	17	17	22	35	28	114	251
05. Forestry, Fishing, & Hunting	2	20	26	38	131	198	243	186	756	1,601
06. Oil & Gas	9	45	54	75	207	353	550	441	1,581	3,315
07. Coal	0	0	0	1	2	5	3	2	4	18
08. Other Mining	4	10	15	62	213	465	294	216	311	1,589
09. Biomass electricity generation	1	6	7	10	25	41	67	60	208	426
10-11. Coal-fired and Gas-fired electricity generation	18	50	53	71	207	361	574	680	1,364	3,378
12. Hydroelectric generation	1	5	5	7	21	41	68	87	150	386
13. Nuclear electricity generation	5	14	15	21	62	116	186	242	399	1,061
14. Renewable electricity generation	10	27	29	38	105	161	249	236	703	1,558
15. Electricity distribution	5	15	16	21	61	105	165	192	399	979
16. Natural gas distribution	8	23	25	45	170	516	904	1,634	1,080	4,404

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
17. Water and sewage services	3	14	16	22	62	118	197	243	467	1,142
18. Residential Construction	64	313	493	1,250	3,343	6,603	6,417	5,301	11,173	34,957
19. Highway Construction	6	30	71	271	741	1,580	1,276	1,081	1,225	6,281
20. Other Non-Residential Construction	53	252	589	2,213	6,037	12,858	10,439	8,837	10,304	51,583
21. Highway Maintenance	6	28	61	214	583	1,229	1,026	866	1,140	5,152
22. Other Maintenance	24	116	254	903	2,456	5,190	4,308	3,638	4,680	21,569
23. Food Processing	33	99	886	2,243	2,667	2,638	1,647	1,383	3,239	14,835
24. Beverage & Tobacco Product Manufacturing	13	49	225	662	1,100	1,341	1,023	769	1,811	6,992
25. Textile & Textile Product Manufacturing	1	4	93	180	180	145	84	83	150	920
26. Apparel	2	10	373	554	294	311	283	313	509	2,649
27. Leather & Allied Products	0	0	12	45	24	9	4	5	11	110
28. Wood Product Manufacturing	3	8	106	346	410	331	164	136	246	1,749
29. Paper Mills	5	15	76	243	429	450	245	238	522	2,222
30. Printing & Related Support Activities	4	15	164	439	662	751	335	322	592	3,284
31. Petroleum Refineries	61	169	178	238	651	1,003	1,602	1,270	4,216	9,388
32. Other Petroleum & Coal Products	3	8	9	12	33	58	98	83	217	521
33. Chemicals	175	487	604	1,049	2,553	3,979	4,831	4,739	14,727	33,143
34. Rubber & Plastics	7	21	174	549	703	678	415	428	839	3,815
35. Non-Metallics	6	16	117	604	1,224	1,453	662	551	614	5,246
36. Primary Metal Manufacturing	2	2	35	177	279	260	120	100	87	1,063
37. Fabricated Metal Product	19	58	310	1,372	2,419	3,204	1,444	1,292	2,416	12,535
38. Agriculture Machinery	2	6	12	37	74	118	100	110	234	692
39. Industrial Machinery	1	3	37	185	343	568	373	505	643	2,659
40. Commercial Machinery	4	12	28	100	198	316	251	290	554	1,754
41. Ventilation, Heating & Air-Conditioning	1	4	9	31	62	100	81	92	181	563
42. Metalworking Machinery	1	5	15	60	116	189	142	173	293	995
43. Engines & Turbines	2	5	15	55	107	171	131	156	278	920
44. Other General Purpose Machinery Manufacturing	4	12	30	108	213	341	268	314	580	1,869
45. Computers	97	267	471	1,217	2,759	4,942	5,905	10,644	20,764	47,064
46. Computer Storage Devices	7	20	29	62	147	249	310	487	1,073	2,385
47. Computer Terminals & Other Peripheral Equipment	4	11	23	69	153	283	330	643	1,171	2,686
48. Communications Equipment	6	17	24	46	98	124	154	140	470	1,079
49. Miscellaneous Electronic Equipment	27	73	103	200	423	536	666	606	2,028	4,661
50. Semiconductors & Related Devices	32	87	116	212	464	593	759	664	2,339	5,266
51. Electronic Instruments	8	21	28	53	115	146	184	164	565	1,284
52. Household Equipment, Appliances, and Component Manufacturing	4	12	20	42	84	105	123	121	366	878
53. Motor Vehicle and Parts Manufacturing	12	37	59	186	362	616	663	796	1,625	4,354
54. Aerospace Product & Parts Manufacturing	18	50	131	609	1,087	1,955	1,878	2,612	3,978	12,319

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
55. Railroad Rolling Stock Manufacturing	0	0	1	6	10	18	16	24	32	106
56. Ship & Boat Building	0	1	7	42	71	133	120	183	228	786
57. Other Transportation Equipment Manufacturing	1	2	4	16	29	51	50	67	110	327
58. Furniture & Related Product Manufacturing	2	9	150	472	598	558	294	240	470	2,793
59. Miscellaneous Manufacturing	21	59	206	745	1,279	1,839	1,383	1,820	3,275	10,626
60. Wholesale Trade	168	537	1,748	5,980	10,434	13,799	11,650	11,277	22,705	78,298
61. Air Transport	23	67	98	314	829	2,083	813	784	4,286	9,299
62. Rail Transport	2	6	7	9	61	319	230	166	175	976
63. Water Transport	5	16	37	41	115	205	214	164	448	1,247
64. Truck Transport	8	115	386	2,608	5,022	8,940	2,091	1,838	5,006	26,014
65. Transit and Ground Passenger Transport	7	36	160	736	1,212	889	452	343	1,259	5,093
66. Pipelines	0	2	2	4	18	41	55	56	64	242
67. Other Transportation	21	88	361	1,373	2,277	3,818	2,519	1,502	3,403	15,363
68. Warehousing	8	26	454	1,817	2,880	2,892	927	511	823	10,339
69. Retail Trade	109	543	14,099	23,812	21,508	14,635	9,874	8,232	20,770	113,580
70. Publishing Industries	89	249	310	543	1,434	2,787	3,740	5,547	12,041	26,741
71. Motion Picture & Sound Recording Industry	193	533	930	1,390	2,957	4,521	5,995	5,889	16,264	38,672
72. Broadcasting	58	369	494	767	2,001	3,113	4,806	4,202	14,064	29,875
73. Telecommunications	146	406	478	805	2,334	5,356	6,795	5,959	11,769	34,047
74. Information Services	4	10	29	97	400	1,141	1,937	4,477	7,487	15,581
75. Data Processing Services	1	5	14	60	170	584	940	2,190	3,658	7,623
76. Finance & Banking	232	672	1,152	3,683	8,878	15,548	15,050	17,851	41,160	104,226
77. Real Estate	807	2,622	3,951	7,169	15,264	19,639	25,482	20,864	72,803	168,600
78. Rental & Leasing Services	30	127	361	709	1,381	1,705	1,607	1,309	4,214	11,443
79. Lessors of Nonfinancial Intangible Assets	67	189	199	258	700	967	1,434	1,060	4,668	9,541
80. Professional, Scientific, Technical, Administrative, & Support Services	286	1,331	6,431	18,112	28,506	44,173	43,096	66,401	114,559	322,896
81. Waste Management Services	8	23	117	359	822	1,105	896	358	741	4,430
82. Education Services	13	74	1,302	8,120	17,375	27,838	26,785	31,787	14,526	127,820
83. Health Care & Social Assistance	86	445	11,087	19,316	30,097	34,633	25,394	43,896	50,932	215,886
84. Arts, Entertainment & Recreation	51	245	2,247	3,488	3,576	4,256	3,990	3,121	9,099	30,074
85. Accommodations	21	70	1,450	3,291	3,051	2,130	1,168	941	1,973	14,095
86. Eating & Drinking Places	71	276	14,388	20,236	8,741	5,122	3,578	2,267	8,540	63,220
87. Other Services	-1	317	2,809	5,868	6,821	8,652	7,475	6,237	15,669	53,847
88. Owner-Occupied Dwellings	461	1,265	1,317	1,674	4,570	6,220	9,175	6,561	29,850	61,094
89. Government Enterprises	35	95	142	365	1,202	2,820	3,175	3,939	3,259	15,033
90. State & Local Government	9,229	24,878	15,481	13,834	23,560	34,338	34,865	36,254	29,481	221,919
91. Federal Government	15,277	41,406	25,560	20,684	31,027	34,537	31,426	20,617	50,210	270,743
Total	**28,343**	**79,882**	**117,735**	**190,410**	**277,948**	**371,097**	**344,198**	**375,087**	**691,027**	**2,475,727**

Table 11. Total Personal Income Distribution Coefficient Matrix, 2018

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
01. Crops	0.001	0.008	0.161	0.198	0.081	0.073	0.097	0.079	0.303	1.000
02. Poultry & Eggs	0.001	0.009	0.122	0.151	0.073	0.077	0.113	0.092	0.361	1.000
03. Livestock	0.001	0.012	0.065	0.081	0.066	0.086	0.136	0.109	0.444	1.000
04. Other Livestock	0.002	0.013	0.054	0.069	0.067	0.089	0.140	0.110	0.456	1.000
05. Forestry, Fishing, & Hunting	0.002	0.013	0.016	0.023	0.082	0.124	0.152	0.116	0.472	1.000
06. Oil & Gas	0.003	0.013	0.016	0.023	0.063	0.107	0.166	0.133	0.477	1.000
07. Coal	0.003	0.008	0.011	0.037	0.123	0.260	0.179	0.133	0.247	1.000
08. Other Mining	0.002	0.006	0.009	0.039	0.134	0.292	0.185	0.136	0.195	1.000
09. Biomass electricity generation	0.003	0.014	0.017	0.023	0.060	0.095	0.158	0.142	0.488	1.000
10-11. Coal-fired and Gas-fired electricity generation	0.005	0.015	0.016	0.021	0.061	0.107	0.170	0.201	0.404	1.000
12. Hydroelectric generation	0.004	0.012	0.014	0.019	0.056	0.106	0.175	0.225	0.390	1.000
13. Nuclear electricity generation	0.005	0.014	0.014	0.020	0.058	0.109	0.175	0.228	0.376	1.000
14. Renewable electricity generation	0.006	0.018	0.019	0.024	0.068	0.103	0.160	0.151	0.452	1.000
15. Electricity distribution	0.006	0.015	0.016	0.022	0.063	0.107	0.169	0.196	0.408	1.000
16. Natural gas distribution	0.002	0.005	0.006	0.010	0.039	0.117	0.205	0.371	0.245	1.000
17. Water and sewage services	0.003	0.012	0.014	0.019	0.054	0.103	0.173	0.213	0.409	1.000
18. Residential Construction	0.002	0.009	0.014	0.036	0.096	0.189	0.184	0.152	0.320	1.000
19. Highway Construction	0.001	0.005	0.011	0.043	0.118	0.252	0.203	0.172	0.195	1.000
20. Other Non-Residential Construction	0.001	0.005	0.011	0.043	0.117	0.249	0.202	0.171	0.200	1.000
21. Highway Maintenance	0.001	0.006	0.012	0.042	0.113	0.238	0.199	0.168	0.221	1.000
22. Other Maintenance	0.001	0.005	0.012	0.042	0.114	0.241	0.200	0.169	0.217	1.000
23. Food Processing	0.002	0.007	0.060	0.151	0.180	0.178	0.111	0.093	0.218	1.000
24. Beverage & Tobacco Product Manufacturing	0.002	0.007	0.032	0.095	0.157	0.192	0.146	0.110	0.259	1.000
25. Textile & Textile Product Manufacturing	0.001	0.004	0.101	0.196	0.196	0.158	0.091	0.090	0.163	1.000
26. Apparel	0.001	0.004	0.141	0.209	0.111	0.118	0.107	0.118	0.192	1.000
27. Leather & Allied Products	0.000	0.000	0.108	0.413	0.218	0.082	0.034	0.045	0.099	1.000
28. Wood Product Manufacturing	0.002	0.004	0.060	0.198	0.234	0.189	0.094	0.078	0.141	1.000
29. Paper Mills	0.002	0.007	0.034	0.109	0.193	0.203	0.110	0.107	0.235	1.000
30. Printing & Related Support Activities	0.001	0.004	0.050	0.134	0.202	0.229	0.102	0.098	0.180	1.000
31. Petroleum Refineries	0.007	0.018	0.019	0.025	0.069	0.107	0.171	0.135	0.449	1.000
32. Other Petroleum & Coal Products	0.005	0.015	0.017	0.023	0.064	0.111	0.188	0.160	0.416	1.000
33. Chemicals	0.005	0.015	0.018	0.032	0.077	0.120	0.146	0.143	0.444	1.000
34. Rubber & Plastics	0.002	0.006	0.046	0.144	0.184	0.178	0.109	0.112	0.220	1.000
35. Non-Metallics	0.001	0.003	0.022	0.115	0.233	0.277	0.126	0.105	0.117	1.000
36. Primary Metal Manufacturing	0.002	0.002	0.033	0.166	0.263	0.244	0.113	0.094	0.082	1.000

37. Fabricated Metal Product	0.001	0.005	0.025	0.109	0.193	0.256	0.115	0.103	0.193	1.000
38. Agriculture Machinery	0.003	0.008	0.017	0.053	0.108	0.170	0.144	0.159	0.338	1.000
39. Industrial Machinery	0.000	0.001	0.014	0.070	0.129	0.214	0.140	0.190	0.242	1.000
40. Commercial Machinery	0.002	0.007	0.016	0.057	0.113	0.180	0.143	0.166	0.316	1.000
41. Ventilation, Heating & Air-Conditioning	0.002	0.007	0.016	0.056	0.111	0.177	0.144	0.164	0.322	1.000
42. Metalworking Machinery	0.001	0.005	0.015	0.061	0.117	0.190	0.143	0.174	0.295	1.000
43. Engines & Turbines	0.002	0.006	0.016	0.059	0.116	0.186	0.143	0.170	0.302	1.000
44. Other General Purpose Machinery Manufacturing	0.002	0.006	0.016	0.058	0.114	0.183	0.143	0.168	0.310	1.000
45. Computers	0.002	0.006	0.010	0.026	0.059	0.105	0.125	0.226	0.441	1.000
46. Computer Storage Devices	0.003	0.008	0.012	0.026	0.062	0.104	0.130	0.204	0.450	1.000
47. Computer Terminals & Other Peripheral Equipment	0.001	0.004	0.009	0.026	0.057	0.105	0.123	0.239	0.436	1.000
48. Communications Equipment	0.006	0.016	0.022	0.043	0.091	0.115	0.143	0.130	0.435	1.000
49. Miscellaneous Electronic Equipment	0.006	0.016	0.022	0.043	0.091	0.115	0.143	0.130	0.435	1.000
50. Semiconductors & Related Devices	0.006	0.017	0.022	0.040	0.088	0.113	0.144	0.126	0.444	1.000
51. Electronic Instruments	0.006	0.016	0.022	0.041	0.089	0.114	0.144	0.128	0.440	1.000
52. Household Equipment, Appliances, and Component Manufacturing	0.005	0.014	0.022	0.048	0.096	0.119	0.140	0.138	0.417	1.000
53. Motor Vehicle and Parts Manufacturing	0.003	0.008	0.014	0.043	0.083	0.141	0.152	0.183	0.373	1.000
54. Aerospace Product & Parts Manufacturing	0.001	0.004	0.011	0.049	0.088	0.159	0.152	0.212	0.323	1.000
55. Railroad Rolling Stock Manufacturing	0.001	0.002	0.009	0.052	0.090	0.165	0.153	0.224	0.305	1.000
56. Ship & Boat Building	0.000	0.001	0.008	0.054	0.091	0.170	0.153	0.232	0.291	1.000
57. Other Transportation Equipment Manufacturing	0.002	0.005	0.011	0.048	0.087	0.155	0.152	0.205	0.335	1.000
58. Furniture & Related Product Manufacturing	0.001	0.003	0.054	0.169	0.214	0.200	0.105	0.086	0.168	1.000
59. Miscellaneous Manufacturing	0.002	0.006	0.019	0.070	0.120	0.173	0.130	0.171	0.308	1.000
60. Wholesale Trade	0.002	0.007	0.022	0.076	0.133	0.176	0.149	0.144	0.290	1.000
61. Air Transport	0.002	0.007	0.011	0.034	0.089	0.224	0.087	0.084	0.461	1.000
62. Rail Transport	0.002	0.006	0.007	0.009	0.062	0.327	0.236	0.171	0.179	1.000
63. Water Transport	0.004	0.013	0.030	0.033	0.093	0.164	0.172	0.132	0.360	1.000
64. Truck Transport	0.000	0.004	0.015	0.100	0.193	0.344	0.080	0.071	0.192	1.000
65. Transit and Ground Passenger Transport	0.001	0.007	0.031	0.144	0.238	0.175	0.089	0.067	0.247	1.000
66. Pipelines	0.001	0.006	0.010	0.016	0.076	0.170	0.228	0.229	0.264	1.000
67. Other Transportation	0.001	0.006	0.023	0.089	0.148	0.249	0.164	0.098	0.222	1.000
68. Warehousing	0.001	0.002	0.044	0.176	0.279	0.280	0.090	0.049	0.080	1.000
69. Retail Trade	0.001	0.005	0.124	0.210	0.189	0.129	0.087	0.072	0.183	1.000
70. Publishing Industries	0.003	0.009	0.012	0.020	0.054	0.104	0.140	0.207	0.450	1.000

71. Motion Picture & Sound Recording Industry	0.005	0.014	0.024	0.036	0.076	0.117	0.155	0.152	0.421	1.000
72. Broadcasting	0.002	0.012	0.017	0.026	0.067	0.104	0.161	0.141	0.471	1.000
73. Telecommunications	0.004	0.012	0.014	0.024	0.069	0.157	0.200	0.175	0.346	1.000
74. Information Services	0.000	0.001	0.002	0.006	0.026	0.073	0.124	0.287	0.481	1.000
75. Data Processing Services	0.000	0.001	0.002	0.008	0.022	0.077	0.123	0.287	0.480	1.000
76. Finance & Banking	0.002	0.006	0.011	0.035	0.085	0.149	0.144	0.171	0.395	1.000
77. Real Estate	0.005	0.016	0.023	0.043	0.091	0.116	0.151	0.124	0.432	1.000
78. Rental & Leasing Services	0.003	0.011	0.032	0.062	0.121	0.149	0.140	0.114	0.368	1.000
79. Lessors of Nonfinancial Intangible Assets	0.007	0.020	0.021	0.027	0.073	0.101	0.150	0.111	0.489	1.000
80. Professional, Scientific, Technical, Administrative, & Support Services	0.001	0.004	0.020	0.056	0.088	0.137	0.133	0.206	0.355	1.000
81. Waste Management Services	0.002	0.005	0.026	0.081	0.186	0.249	0.202	0.081	0.167	1.000
82. Education Services	0.000	0.001	0.010	0.064	0.136	0.218	0.210	0.249	0.114	1.000
83. Health Care & Social Assistance	0.000	0.002	0.051	0.089	0.139	0.160	0.118	0.203	0.236	1.000
84. Arts, Entertainment & Recreation	0.002	0.008	0.075	0.116	0.119	0.142	0.133	0.104	0.303	1.000
85. Accommodations	0.001	0.005	0.103	0.234	0.216	0.151	0.083	0.067	0.140	1.000
86. Eating & Drinking Places	0.001	0.004	0.228	0.320	0.138	0.081	0.057	0.036	0.135	1.000
87. Other Services	0.000	0.006	0.052	0.109	0.127	0.161	0.139	0.116	0.291	1.000
88. Owner-Occupied Dwellings	0.008	0.021	0.022	0.027	0.075	0.102	0.150	0.107	0.489	1.000
89. Government Enterprises	0.002	0.006	0.009	0.024	0.080	0.188	0.211	0.262	0.217	1.000
90. State & Local Government	0.042	0.112	0.070	0.062	0.106	0.155	0.157	0.163	0.133	1.000
91. Federal Government	0.056	0.153	0.094	0.076	0.115	0.128	0.116	0.076	0.185	1.000
Total	**0.011**	**0.032**	**0.048**	**0.077**	**0.112**	**0.150**	**0.139**	**0.152**	**0.279**	**1.000**

4.4. Model Linkages

4.4.1. Linking Transportation Network Model and TERM Model

In this sub-section, we present the steps that can be adopted to link the Transportation Network Model and the TERM Multi-region CGE Model.

A number of approaches to connecting models are available. The best approach depends on the objectives of the research, professional standards, and limitations of various resources such as data, time and funding. Our objective is to develop an operational connection of models that can yield accurate estimates of disaster consequences and resilience to them within the limits of the current project. Disaster consequences in this case include impacts on transportation flows, distance, and costs, and economic impacts in the aggregate and across sectors and income groups, all in the Southern California Region. Socioeconomic consequences are measured in terms of income and employment and resilience is measured in terms of its ability to improve traffic flow, reduce congestion and reduce business interruption.

Connections between models have in recent years been characterized as either “hard” or “soft” linkages (see, e.g., Kiuila and Rutherford, 2013; U.S. EPA, 2017). Hard linkages pertain to the ultimate of connectivity of fully integrating two or more models in terms of structure and computation. Soft linkages refer to keeping the model separate but connecting them by at least a one-way flow of information, or outputs, from one to another. More extensive soft linkages call for a two-way flow of information and even an iterative exchange and overall system solution.

Given the complicated nature of both the CGE and the TN Models, hard linkage is not possible within the scope of this project.[8] However, the research team has worked on building several types of soft linkages. These are facilitated by the fact that the two models have aspects of transportation demand and supply in common.

The linkages between the two models have been established using the following approaches:

1. Reduced seaport capacity caused by a major earthquake is estimated based on the damages of the buildings and facilities at the ports simulated using the FEMA's hazard loss estimation software -- HAZUS. The direct impacts on import and export flows through the ports are estimated by linking the damaged terminal buildings to the main cargo categories handled by these facilities.

2. Damages to the bridges and road network are estimated using image-based geometric models and structure-specific fragility functions based on these image-based models (Cetiner et al., 2019) or HAZUS (FEMA, 2013). The TN model is then used to specify the likely reconfiguration of freight traffic given physical damage to the road network and changes in commodity supply and demand.

3. We then use the TN Model to estimate the increased distance and time of delivering freight to its destinations within the LA Metro Region and between LA Metro and Rest of California. The increased freight delivery distance and time is converted into increased transportation costs.

4. Increase in transportation costs, reductions in commodity supply caused by the port disruptions, and business interruptions caused by the general building damages of the scenario earthquake are used as input in the CGE model to determine the general equilibrium (broad multiplier effects including both the implications of quantity and price changes) throughout the region.

5. Various transportation resilience factors (such as faster repair and recovery of critical corridors) are simulated using the TN Model to estimate the improvements that these types of disaster resilience can bring about. The effects of various economic resilience tactics related to port disruptions and general building damages (such as ship re-routing, excess capacity, input conservation, use of inventories, relocation) are estimated in terms of how they can help reduce the magnitude of the direct impacts.

6. The CGE model is used to estimate the improvements that these types of disaster resilience can bring about by comparing the estimated economic losses before and after the incorporation of the various resilience tactics.

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[8] There exist examples of hard linkages in this topic area. For example, Cho et al. (2001) developed extensive linkages between an economic and transportation model. However, the economic component was an input-output (I-O) model, which is much less sophisticated and much less accurate than the CGE approach. The limitations are due to the inherent linearity of I-O models and their inability to deal with cost and price changes, such as those likely caused by transportation disruptions.

4.4.2. Linking the TERM Model and MSIDM

Like all computable general equilibrium (CGE) models, the TERM Model (Horridge et al., 2005; Wittwer, 2012; CoPS, 2019) divides the economy into a large number of mutually exclusive and completely exhaustive producing sectors. In the version of the model we are using, there are 97 sectors, which is in the high-range of the degree of sectoral detail of most CGE models in use today. The reason sectoral detail is important is that practically every shock to the economy, whether it be a natural disaster, change in regulation, or infusion of government spending (including post-disaster assistance), affects the various sectors in the economy differentially. For the focus of our study, seaport activity and ground transportation are heavily affected directly, as are other major sectors that are likely to incur relatively more damage than others, such as factories with sensitive equipment, sectors whose companies are located in high-rise buildings, and sectors highly dependent on infrastructure in general. Moreover, all the sectors directly affected have different multipliers or, more broadly, general equilibrium effects, that are transmitted through the supply chain within the region and beyond.

Not only are there variations in the distribution of economic activity, but also variations in the distribution of income stemming from an external shock. In the case of earthquakes, households are directly affected through damage to homes and their contents, but also through changes in production activity. Those workers employed by companies most affected directly and indirectly by, say, an earthquake, will be affected more than others. However, when we speak of income distribution impacts, we are referring to the distribution of impacts across income groups and not only across sectors. Economic sectors differ in their profile (distribution) of income payments across income brackets. The underlying factors affecting this distribution include the capital-labor ratio (which affects the relative proportion of wages/salaries versus capital-related income), debt-equity ratio (which affects relative proportions of dividend and interest payments), idiosyncratic features (only some sectors have significant payments of rents or royalties). Drilling down deeper, the skill levels of employees are rewarded differentially, and the sectoral investors differ across income brackets (e.g., retirees and those in higher income-brackets invest more heavily in public utilities, owing primarily to economic stability in these sectors for the former group and to preferential tax treatment for the latter). Complicating the picture in the case of general equilibrium analysis, changes in the rates of factor returns (wages/salaries and capital-related income), as well as changes in the shares of income to these two general groups also affect the distribution of income.

Linkage of the two aspects of our economic impact model involves two steps. The initial one is rather straightforward given the commonality of one key aspect of both modules -- the disaggregation according to economic sector. That is, the sectoral classification is the same for both. Thus, 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 initial earthquake damages, initial changes in transportation patterns, and/or optimal transportation route reconfigurations 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 initial distribution and the changed distribution can be compared by a number of metrics, such as the Gini coefficient, to determine whether the income distribution has been worsened or improved. We acknowledge some limitations of single-parameter metrics like the Gini coefficient, so we will make use of graphical approaches of the entire distribution such as the Lorenz curve and will also utilize multi-parameter income distribution metrics as well.

The second step is more complicated, in that it takes into account changes in two other major factors influencing the income distribution: the changes in capital-labor ratio and changes in factor returns.

Both of these stimuli can be calculated by the TERM Model. In turn, they are used to adjust the MSIDM. The adjustment process involves returning to the basic building blocks of the MSIDM, such as the Wage/Salary/Employee Compensation Matrix and the Capital-Related Income Matrix. The change in capital-labor ratio is reflected by the change in the relative weights of these two matrices, and the change in factor returns also affects the relative weights. This yields a new MSIDM to be applied to the vector of sectoral income changes in a manner similar to that described in the previous paragraph. Hence, the bottom-line income distribution impacts are determined by this second set of calculations. We note one limitation of the analysis, in that it omits any feedback effects of changes in the income distribution on economic activity. This would take place because the distribution of purchase of goods and services by households differs across income brackets. For example, relatively greater distributional impacts on high-income groups will reduce the purchases of luxury goods relatively more than the base income distribution. However, studies have shown that this feedback effect on the bottom-line income distribution is typically much smaller than the direct and indirect impacts resulting from changes in the sectoral mix, capital-labor ratio, and rates of factor returns.

4.4.3. Integrated Modeling System

Figure 5 displays how the various analytical models are integrated in this study. In general, formal hazard analysis results in single or multi-hazard settings are required to realistically simulate a disruption in the network and in the economy. For this study, hazard characterization and damage assessment results from a concurrent work (Koc et al., 2020), namely damage and recovery of bridges in the case of a simulated earthquake scenario were taken to inform the transportation systems analysis. Additionally, the same scenario was simulated to estimate damages to other buildings (i.e., FEMA HAZUS, General Building Stock) and ports. These hazard results inform both the transportation system analysis (See 4.1.2.) and socioeconomic impact analysis.

5. Disaster Scenario and Methods to Estimate Disaster Damages

To illustrate the working of the integrated transportation-socioeconomic impact model, we use the results of a simulated scenario earthquake, a Mw 7.3 earthquake caused by a rupture of the Palos Verdes Connected fault system at an epicentral distance 1.4 km off the Ports of Los Angeles and Long Beach as a case study[9]. This scenario event, identified by disaggregating the probabilistic seismic hazard in the area for 975-year return period, was simulated. Effects of the earthquake are limited to ground shaking only. In this section we discuss the methodology used for additional hazard characterization and damage assessment carried out for (1) bridges, (2) ports and (2) general buildings. In transportation systems analyses, bridges are regarded as the most critical segments of a road network due to lower redundancy associated with them. The potential damages and disruptions to Ports of Los Angeles and Long Beach are essential to the case study because they are the main origin and destination of internationally traded commodities in the region.

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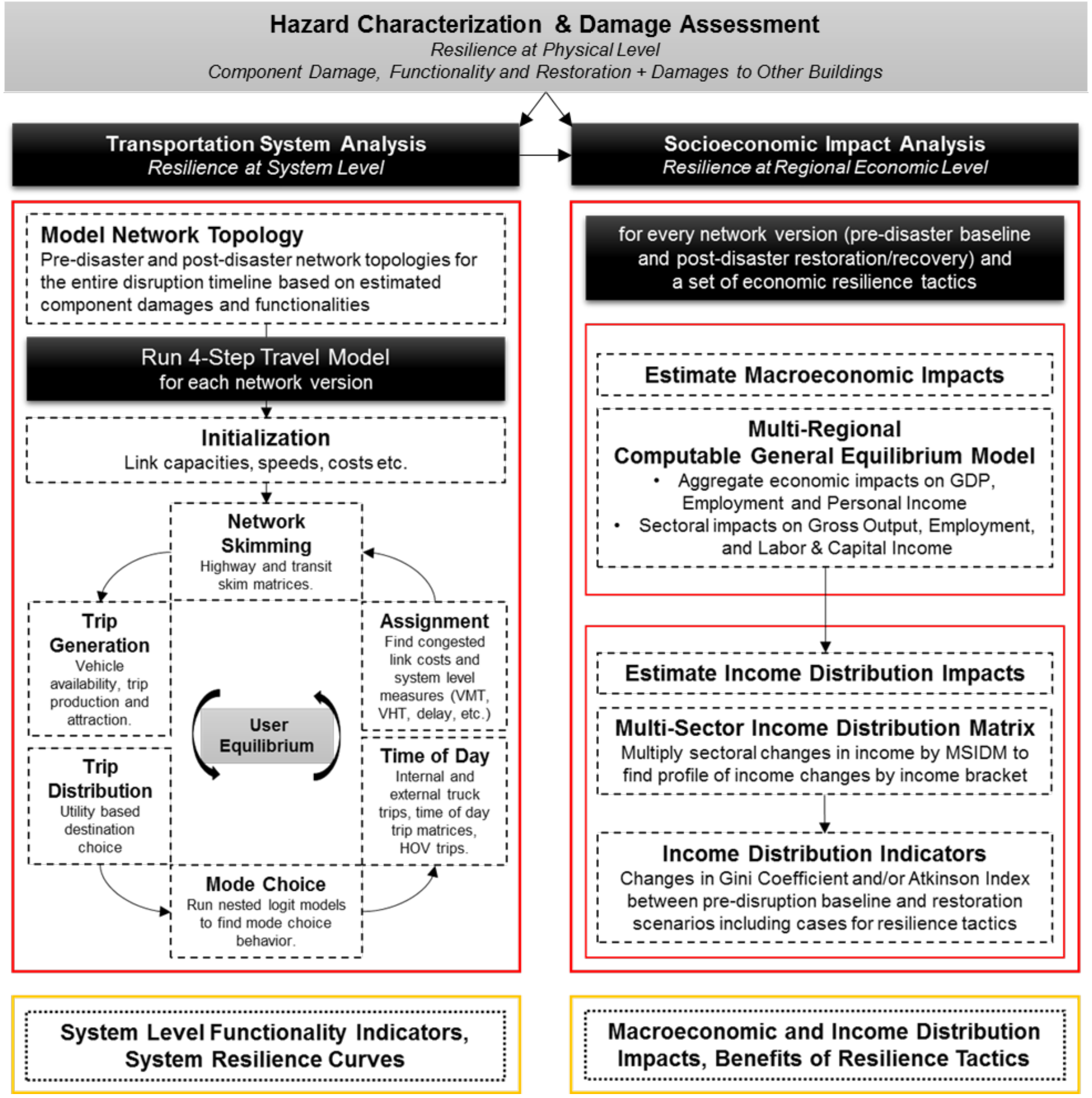
[9] Note that the seismic hazard scenario was originally characterized by the authors' collaborators at UCLA CEE's Taciroglu Research Group for a concurrent study on comprehensive resilience assessment for transportation systems in urban areas (Koc et al., 2020). The same reference provides detailed discussions on how a computer vision enabled methodology is used to estimate damages to and restoration of bridges.

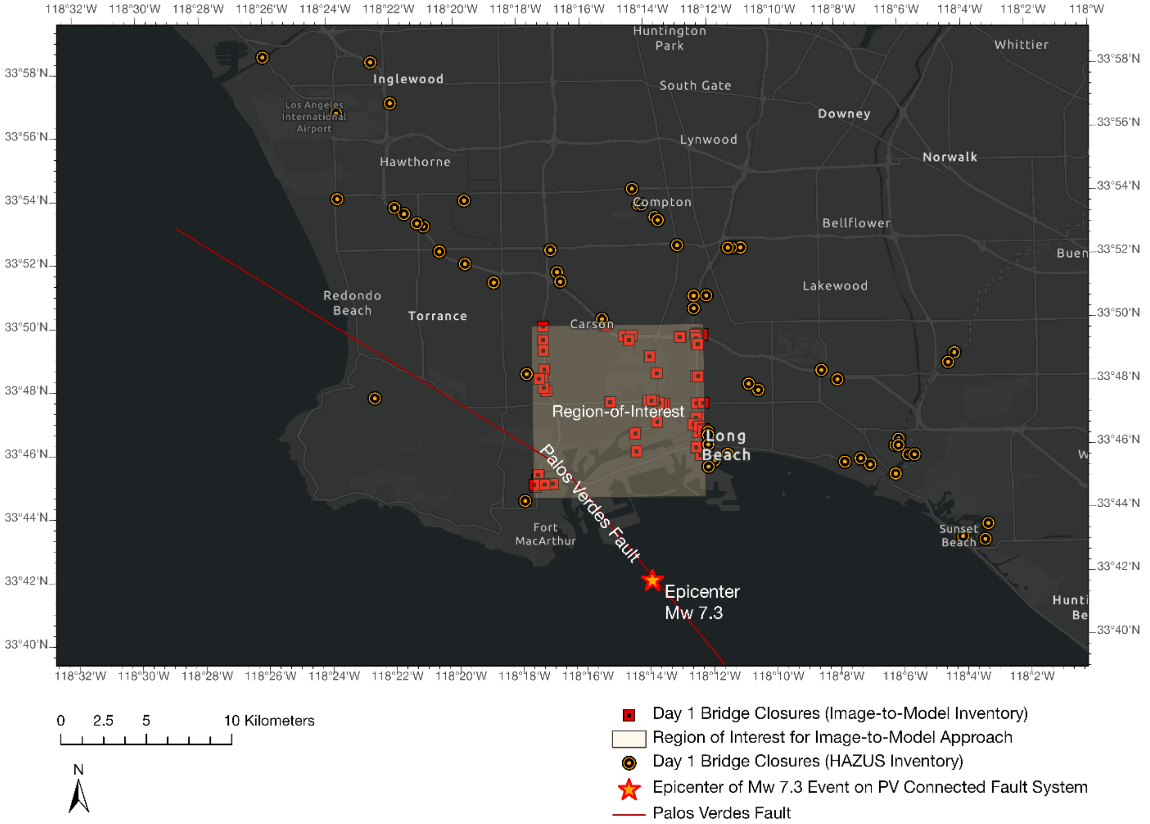
Figure 5. Integration of Transportation and Economic Models



5.1. Method to Estimate Damages to Bridges

98 bridges in a region of interest around the ports (See Figure 6) were modeled by the authors' collaborators using a computer vision enabled methodology which is beyond the scope here. The remainder of the bridge inventory in the region was complemented from FEMA's HAZUS software (FEMA, 2010). Through an assessment of the fragility functions corresponding to this hybrid inventory, damage state probabilities for the commonly used 5 damage states (None, Slight, Moderate, Extensive, and Complete) were estimated. Damage state results tie to the restoration functions given in HAZUS that allow the estimation of downtimes. Consequently, bridge closures can be implemented in various network versions that collectively represent the disruption and recovery of the transportation network under mentioned scenario earthquake. Figure 6 shows bridge closures on Day 1 after the scenario event. The recovery/re-open time path of the damaged bridges is presented in Section 6.3.

Figure 6. Modeled Bridge Closures on Day 1



Note: see more details in Koc et al. (2020)

5.2. Method to Estimate Damages to Ports of Los Angeles and Long Beach

To simulate the Mw 7.3 earthquake scenario, the researchers utilized HAZUS 4.2 (FEMA 2010), FEMA's hazard loss estimation software with the default building inventory data on ports and harbors to estimate damage and functionality at the Ports of Los Angeles and Long Beach. Probabilities for each damage state as well as the expected functionality levels throughout the recovery timeline are estimated for 171 facilities in total for both ports (berths, terminals, etc.). We then use official facility maps published by the port authorities to manually classify the berths in the HAZUS inventory into main cargo categories handled by the facilities such as automobile, containerized cargo, dry bulk, liquid bulk, etc., to link the facility downtimes to disruptions of imported and exported commodity flows.

5.3. Method to Estimate General Building Damages

HAZUS has a detailed loss estimation methodology for the damages and the direct losses resulting from the vulnerability of the general building stock (GBS) to the simulated event. GBS includes residential, commercial, industrial, agricultural, religious, government, and educational buildings, and the damage state probability of the general building stock is computed at the centroid of the census tract. The damage states for each building type are linked to the default economic data supplied within HAZUS (e.g., structural repair costs for each of the damage states, model building types and occupancies, contents damage as a function of damage state, etc.) to estimate the direct economic losses. Detailed discussions on the building damage and loss estimation methodology can be found in the corresponding technical manual published by FEMA (FEMA, 2012).

The database behind the approach stores building information at the census tract level for the specific occupancy classes listed in Table 12. For each census tract and per each occupancy class, structural and nonstructural cost of repair or replacement, loss of contents, business inventory loss, relocation costs, business income loss, employee wage loss and loss of rental income are estimated. Definitions of each loss category are provided in the cited HAZUS technical manual. To inform the TERM Model, all such results are first aggregated up to the county level of detail. Then the percentage of building/content damages are calculated for the 3-county LA Metro Region.

Table 12. Specific Occupancy Classes for the General Building Stock in HAZUS

RES1	Single Family Dwelling	**IND1**	Heavy
RES2	Mobile Home	**IND2**	Light
RES3	Multi Family Dwelling	**IND3**	Food/Drugs/Chemicals
RES4	Temporary Lodging	**IND4**	Metals/Minerals Processing
RES5	Institutional Dormitory	**IND5**	High Technology
RES6	Nursing Home	**IND6**	Construction
AGR1	Agriculture	**COM1**	Retail Trade
REL1	Church/Non-Profit	**COM2**	Wholesale Trade
GOV1	General Services	**COM3**	Personal and Repair Services
GOV2	Emergency Response	**COM4**	Professional/Technical Services
EDU1	Grade Schools	**COM5**	Banks
EDU2	Colleges/Universities	**COM6**	Hospital
		COM7	Medical Office/Clinic
		COM8	Entertainment and Recreation
		COM9	Theaters
		COM10	Parking

6. Direct Impacts of the Simulated Earthquake Scenario

6.1. Disruption and Recovery of Regional Transportation

6.1.1 Base Case Disruption and Recovery of Regional Transportation

The methodology for refining the network model was discussed in Deliverable 1 – Task 2. Based on the results from the seismic hazard analysis for the mentioned scenario event, 6 network versions in total (for days 0, 1, 7, 30, 90 and 104 after the earthquake event) were modeled and the simulations for each version was completed under fixed travel demand assumptions to quantify the disruption and recovery of transportation in the region. This pertains to the solution of the complete traffic distribution and assignment problem for each network version[10]. Precisely, 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. For example, Figure 6 shows the closed bridges on the first day after the earthquake (Day 1 network). Simulating every network version for the corresponding bridge closures, system level functionality indicators, such as Total Travel Time (Vehicle-Hours-Traveled), Total Travel Distance (Vehicle-Miles-Traveled) and Delay, were quantified to investigate the disruption.

The quantification of the mentioned indicators allow the authors to calculate system functionality and its resilience to the scenario event as discussed in 4.1.1. Figure 7 shows the reconfigured vehicle flow for part of the study region for Day 1, and Figure 8 shows system functionality *Q(t)* for the entire study region as well as the 3 largest counties, Los Angeles, Orange and Riverside. Significant disruptions in regional mobility are observed, particularly in the Day 1 network, in which 147 bridges are deemed closed to service. During the first week, we estimate a total of approximately 850,000 hours/day additional travel time spent in traffic, which corresponds to a 6.52% decrease of TTT (Total Travel Time) based functionality in the study region. As Figure 8 demonstrates, Los Angeles County burdens most of this functionality loss with a 11.81% loss in functionality.

The estimated disruption (and the recovery) in the regional transportation system is conveyed to economic analysis at the level of the regional breakdown in the TERM Model. TERM regions used for the study are L.A. Metropolitan Area (MSA) (including Los Angeles, Orange, and Riverside counties) and Rest of CA. The transportation disruption results estimated at a much higher resolution (at the Traffic Analysis Zone level[11]) are aggregated up to this 2-region breakdown. Since TTD (Total Travel Distance) based functionality indicates only marginal changes given the high redundancy in the dense urban network[12], we use changes in TTT (Total Travel Time) directly as the indicator of changes in transportation costs when linking transportation results to economic impact analysis. This is expressed as a percent increase in labor costs that constitute the larger share, as well as fuel, operation and maintenance costs. For this TTT based functionality, results for every network version are benchmarked to their baseline levels (Day 0) and the decreasing relative functionality is perceived as a percentage increase in transportation costs. These estimates are provided in Table 13. For instance, during the first week after the scenario event, the intraregional transportation in LA Metro region is estimated to be 9.88% more costly and the interregional transportation between the LA Metro region and Rest of CA is estimated to be 4.94% more costly.

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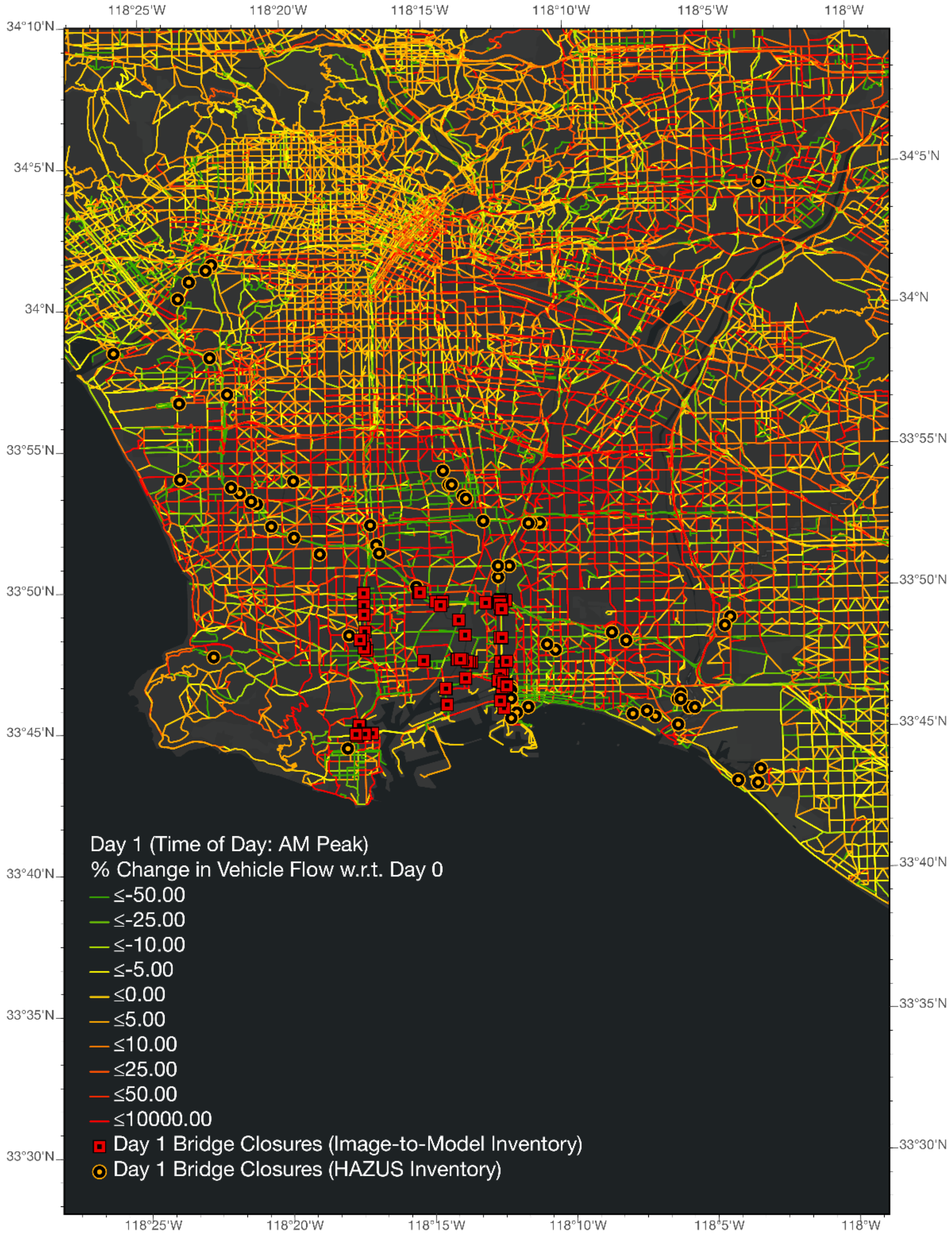
[10] Under fixed demand assumptions, each simulation run takes about 2 days on the proprietary software platform, TransCAD

[11] More than 11000 TAZs are used to model the travel demand in the SCAG region.

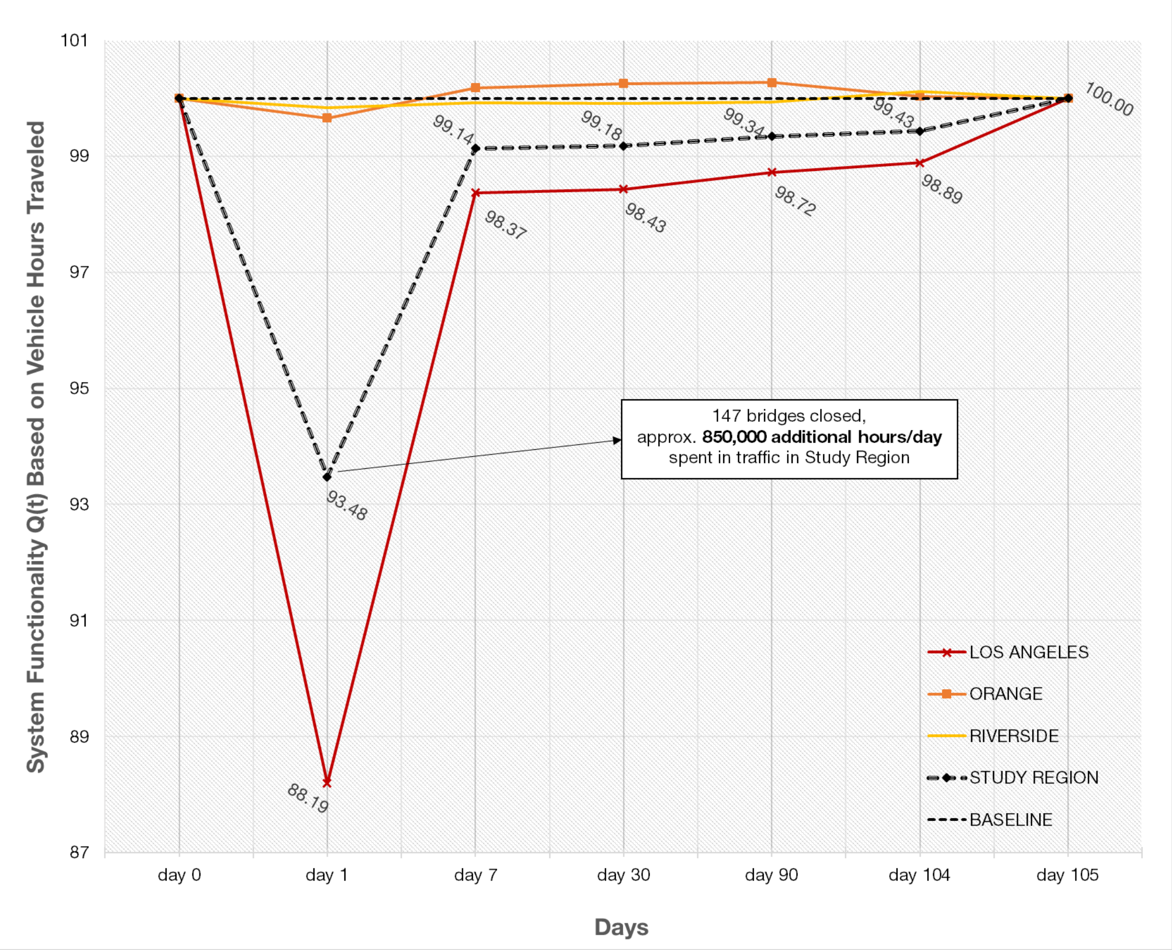
[12] High redundancy enables short detours, and TTD indicators change only marginally, while TTT indicators show a major disruption. In Los Angeles, the dense street networks result in this phenomenon. In other cities, such as San Francisco, closure of a few low redundancy links can result in significant decreases in TTD based functionality.

Figure 7. 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)](https://arcg.is/HjDO8)

Figure 8. Regional System Functionality Q(t)



Based on Vehicle Hours Traveled (VHT) and shown for counties of Los Angeles, Orange and Riverside and entire SCAG region (Study Region)

Note: The above 100% functionality for Riverside is a result of reconfigured flow. Due to major closures on 405S, Riverside receives less traffic flow, which increases the travel time-based functionality.

Table 13. Percentage Increase in Transportation Costs for Intraregional and Interregional Transportation between LA Metro Region and Rest of CA

	DAYS 1-7	
FROM / TO	**LA METRO**	**REST OF CA**
LA METRO	9.88	4.94
	DAYS 7-30	
FROM / TO	**LA METRO**	**REST OF CA**
LA METRO	1.34	0.67
	DAYS 30-90	
FROM / TO	**LA METRO**	**REST OF CA**
LA METRO	1.28	0.64
	DAYS 90-104	
FROM / TO	**LA METRO**	**REST OF CA**
LA METRO	1.04	0.52
	DAYS 104-105	
FROM / TO	**LA METRO**	**REST OF CA**
LA METRO	0.92	0.46

6.1.2 Understanding Disruption and Recovery of Regional Transportation under Dynamic Resilience Tactics

So far in the report, the resilience of the transportation system—in a 'static resilience' manner—has been automatically integrated in the estimates of system recovery in terms of the transportation system functionality metrics (i.e., VHT, VMT, VHD), by assuming that the trips are loaded on to the degraded transportation network to find new UE (user equilibrium) based solutions to the traffic assignment problem[13]. In contrast, the recovery of the damaged bridges is estimated through the HAZUS restoration functions. In other words, there has been no modeling for the resilience tactics potentially available at the system level that can accelerate the speed of the recovery of the degraded system, i.e., dynamic resilience. In this section, we present results from a testing of such a tactic, specifically a hypothetical intervention by the decision makers to keep 8 bridges open to service on the I405 corridor between the I405/I110 and I405/I10 intersections. For instance, such an intervention could entail the rapid installment of temporary support structures such as shoring systems that are often used in bridge construction[14]. On Day 1 after the scenario earthquake, these 8 bridges on the mentioned corridor were

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[13] In parallel, the assumption that travelers have perfect information about the state of the network is made. Consequently, UE outcomes of the degraded network versions are used to measure system disruption and recovery.

[14] WashDOT, 2001. Rapid Design of Temporary Support Systems for Bridges Damaged by Earthquakes: https://www.wsdot.wa.gov/research/reports/fullreports/542.2.pdf

observed to have estimated functionality levels close 75% which is the closure threshold mentioned in the earlier sections (Please see the green point features in Figure 9 below for these bridges). Due to the lack of data and literature on the dynamic resilience capacities of owners and agencies, as an effort to test a potential tactic, the authors assume that these 8 bridges are kept open on Day 1, hence contributing to a faster recovery for the entire system.

To quantify the contribution of the more rapid opening of the 8 bridges to system functionality during Days 1-7 after the scenario event, the authors reiterated the transportation systems analysis component of the analytical framework mentioned in earlier sections. From the results (See Figure 10), we find a significant improvement to system functionality for this time period in comparison with the transportation system base case where the 8 bridges are closed to service during Week 1. Specifically, there is over a 3% reduction in functionality loss in L.A. County and a reduction of 220,000 hours/day spent in traffic in the study region with respect to the base case. This is all due to the rapid recovery of 8 bridges (out of 147 closures on Day 1) identified in the tactic, which emphasizes the capability to achieve large improvements in resilience strategically.

Figure 9: Bridges Deemed Open under the Dynamic Resilience Tactic between Days 1-7, and Bridges that Remain Closed during the Same Time Period.

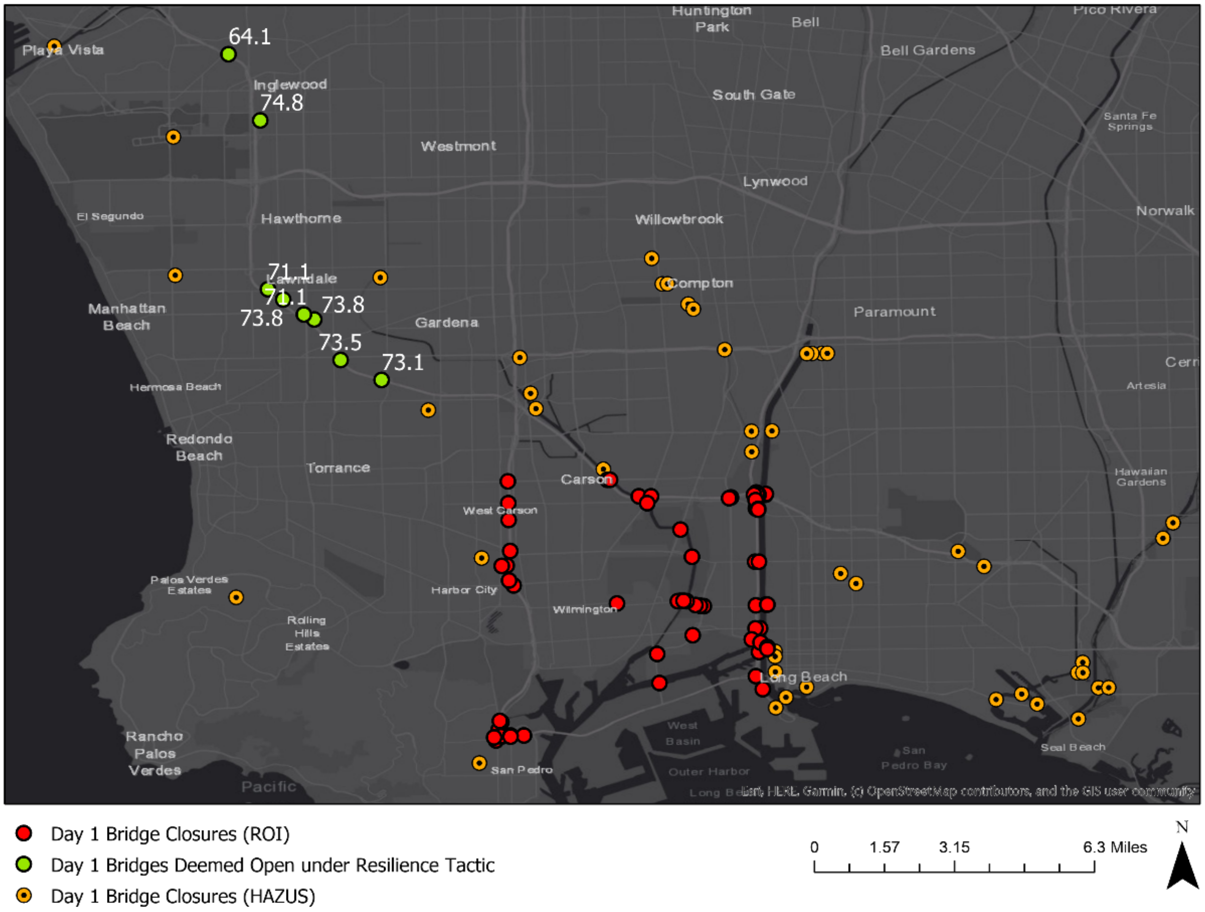
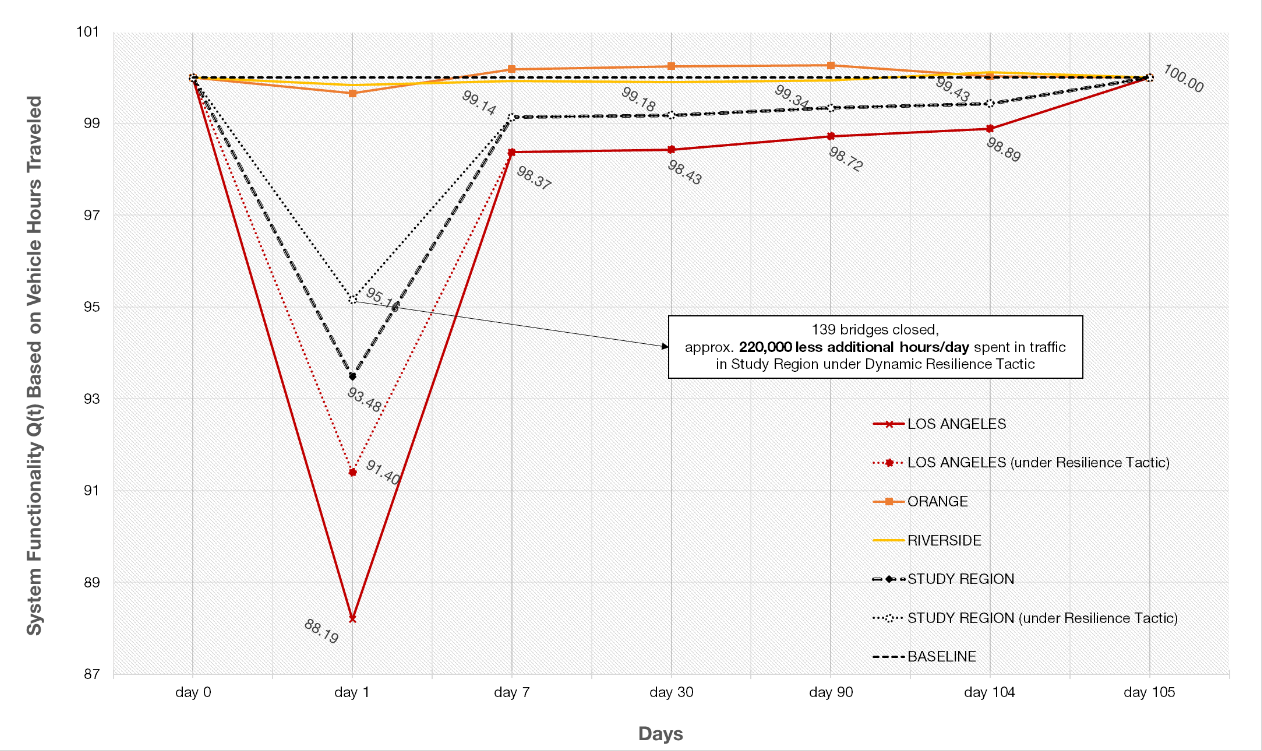


Figure 10. Regional System Functionality Q(t) before and after Resilience Tactic



Note: Based on Vehicle Hours Traveled (VHT) and shown for counties of Los Angeles, Orange and Riverside and entire SCAG region (Study Region)

Table 14 shows the corresponding transportation cost increases (Days 1-7) between the regions of the TERM Model before and after the rapid recovery resilience tactic, which will be used as TERM model inputs in the socioeconomic impact analysis in Section 7.1.

Table 14. (%) Increases in Transportation Costs for Days 1-7 before and after the Resilience Tactic.

	DAYS 1-7 base case		DAYS 1-7 under Resilience Tactic	
FROM / TO	**LA METRO**	**REST OF CA**	**LA METRO**	**REST OF CA**
LA METRO	9.88	4.94	7.27	3.63

6.2. Functionality Loss and Recovery at the Ports of Los Angeles and Long Beach

Due to the special focus on the port complex in this project, instead of making simple assumptions on the remaining functionality at the ports after the scenario event, the authors employed the HAZUS methodology to find estimates of port remaining functionality following the strike of the earthquake as well as its recovery path. HAZUS accommodates a database that provides detailed information (owner, address, coordinates, etc.) about the berths at the ports. However, an industry classification scheme is not given. Therefore, as presented in Section 5.2., we used official facility maps published by the port authorities to manually classify the berths in the HAZUS inventory into main categories of cargos handled by the damaged facilities. This way, functionality loss and recovery information was fed into the TERM Model for 5 different cargo categories (containerized, breakbulk, dry bulk, liquid bulk, automobiles). Table 15 shows these estimates separately for Ports of Los Angeles and Long Beach.

Table 15. Percentage of Port Functionality and Recovery Estimates for Different Cargo-Handling Terminals

Port of Los Angeles							
Facilities	**Day 1**	**Day 3**	**Day 7**	**Day 14**	**Day 30**	**Day 90**	**Day 150**
Container Terminals	51.57	66.47	71.96	72.96	75.74	87.19	100.00
Breakbulk	51.40	66.30	71.80	72.80	75.60	87.10	100.00
Dry Bulk	52.00	66.90	72.40	73.40	76.10	87.40	100.00
Liquid Bulk	51.48	66.38	71.86	72.88	75.64	87.14	100.00
Automobiles	53.40	68.25	73.70	74.70	77.30	88.20	100.00

Port of Long Beach							
Facilities	**Day 1**	**Day 3**	**Day 7**	**Day 14**	**Day 30**	**Day 90**	**Day 150**
Container Terminals	59.73	74.03	79.22	80.05	82.16	91.04	100.00
Breakbulk	60.00	74.26	79.41	80.21	82.32	91.15	100.00
Dry Bulk	58.91	73.34	78.54	79.39	81.56	90.72	100.00
Liquid Bulk	58.38	72.82	78.06	78.88	81.14	90.48	100.00
Automobiles	60.70	74.90	80.00	80.80	82.80	91.40	100.00

6.3. General Building Stock Damages in Greater Los Angeles

Table 16 presents the general building damage data calculated based on the HAZUS earthquake simulation results. The percent building and content losses (last column) is calculated by dividing the sum of dollar losses in building and contents across the three counties of the LA Metro Region by the total exposure values of building stocks. On average, various business sectors in the LA Metro Region experience property damages range from 1.4% to 6.21%. The sectors that experience the highest property damages include High Technology Industry, Food/Drugs/Chemicals Industry, and Wholesale Trade.

In Table 17, we first mapped the percentage property damages from HAZUS occupancy classes to TERM economic sectors. Next, the weighted average recovery period by sector is calculated in Column 4 using the information on building damage states (None, Slight, Moderate, Extensive, and Complete) and the associated recovery time (measured in days) both obtained from HAZUS. In the last column, the percent destruction of capital input is calculated on an annual basis by multiplying the percent building and content losses by the percent of time over one year it takes to recover for each sector.

Table 16. Direct Loss Estimates (Building and Content Losses Only) for the LA Metro Region (Los Angeles, Orange and Riverside Counties)

Occupancy Class	Definition	Building Loss (M $)	Content Loss (M $)	Total Exposure Value (M $)	% Building & Content Loss
AGR1	Agriculture	55,931	21,286	2,692,677	2.87%
COM1	Retail Trade	1,136,455	407,194	36,584,328	4.22%
COM2	Wholesale Trade	1,550,634	547,609	44,862,051	4.68%
COM3	Personal/Repair Services	790,633	297,464	26,745,228	4.07%
COM4	Prof./Technical Services	2,890,156	1,096,050	97,526,179	4.09%
COM5	Banks	133,441	51,242	4,919,510	3.75%
COM6	Hospital	248,196	130,784	12,262,975	3.09%
COM7	Medical office/Clinic	566,333	312,068	18,581,869	4.73%
COM8	Entertainment & Rec.	958,030	342,208	28,844,919	4.51%
COM9	Theaters	33,098	11,575	957,793	4.66%
EDU1	Schools	324,234	129,665	14,528,751	3.12%
EDU2	Colleges/Universities	67,382	42,778	3,914,696	2.81%
GOV1	General Services	145,763	51,576	4,348,859	4.54%
GOV2	Emergency Response	31,361	17,461	1,350,226	3.62%
IND1	Heavy	710,297	394,763	22,782,954	4.85%
IND2	Light	703,994	399,674	22,937,561	4.81%
IND3	Food/Drugs/Chemicals	343,729	194,114	10,176,421	5.29%
IND4	Metals/Minerals Processing	94,854	51,968	2,893,606	5.07%
IND5	High Technology	73,124	41,350	1,843,089	6.21%
IND6	Construction	272,069	102,633	11,127,149	3.37%
REL1	Church/N.P. Offices	489,390	185,631	18,533,206	3.64%
RES1	Single Family Dwelling	11,577,632	3,264,336	1,036,315,753	1.43%
RES2	Mobile Home	390,076	44,305	10,450,711	4.16%
RES3A	Multi Family Dwelling - Duplex	312,416	73,417	14,271,921	2.70%
RES3B	Multi Family Dwelling – 3-4 Units	686,953	161,152	33,351,463	2.54%
RES3C	Multi Family Dwelling – 5-9 Units	1,345,659	315,986	67,098,742	2.48%
RES3D	Multi Family Dwelling – 10-19 Units	1,184,211	278,017	59,984,901	2.44%
RES3E	Multi Family Dwelling – 20-49 Units	1,217,032	285,070	61,599,244	2.44%
RES3F	Multi Family Dwelling – 50+ Units	1,235,564	289,291	63,712,570	2.39%
RES4	Temporary Lodging	264,024	54,375	9,184,425	3.47%
RES5	Institutional Dormitory	492,615	107,345	26,341,777	2.28%
RES6	Nursing Home	43,986	9,603	3,588,936	1.49%
Total		30,369,272	9,711,990	1,774,314,490	2.26%

Note: Building losses include both structural and non-structural losses.

Table 17. General Building Damage for LA Metro Region

TERM Sector #	Short names	% Building & Content Loss	Average Recovery Time (Days)	% Capital Input Destruction on an Annual Basis
1	Crops	2.87%	60	0.47%
2	PoultryEggs	2.87%	60	0.47%
3	Livestock	2.87%	60	0.47%
4	OthLivestock	2.87%	60	0.47%
5	ForestFrsHnt	2.87%	60	0.47%
6	OilGas	5.07%	211	2.93%
7	Coal	5.07%	211	2.93%
8	OtherMining	5.07%	211	2.93%
9	BiomassGen	4.09%	251	2.81%
10	CoalsGen	4.09%	251	2.81%
11	GasGen	4.09%	251	2.81%
12	HydroGen	4.09%	251	2.81%
13	NuclearGen	4.09%	251	2.81%
14	RenewGen	4.09%	251	2.81%
15	ElecDist	4.09%	251	2.81%
16	NatGasDist	4.09%	251	2.81%
17	WaterSewage	4.09%	251	2.81%
18	ResidConstrt	3.37%	164	1.51%
19	OthConstruct	3.37%	164	1.51%
20	HwyBrdgCons	3.37%	164	1.51%
21	OthMaintain	3.37%	164	1.51%
22	MRstreets	3.37%	164	1.51%
23	FoodProc	5.29%	211	3.05%
24	BevTobManu	5.29%	211	3.05%
25	Textiles	4.85%	211	2.80%
26	Apparels	4.81%	211	2.78%
27	LeathFtwr	4.81%	211	2.78%
28	WoodProds	4.85%	211	2.80%
29	PulpPaperPbd	4.85%	211	2.80%
30	Printing	4.81%	211	2.78%
31	PetrolRefine	5.29%	211	3.05%
32	OthPetrolCl	5.29%	211	3.05%
33	Chemicals	5.29%	211	3.05%
34	RubPlastic	4.81%	211	2.78%
35	NonMetMinPrd	5.07%	211	2.93%
36	PrimMetals	5.07%	211	2.93%
37	FabriMetals	4.85%	211	2.80%
38	AgriMachinry	4.85%	211	2.80%
39	IndustrMach	4.85%	211	2.80%
40	CommrcMach	4.85%	211	2.80%
41	AirConHeat	4.85%	211	2.80%
42	MetalWkMach	4.85%	211	2.80%

TERM Sector #	Short names	% Building & Content Loss	Average Recovery Time (Days)	% Capital Input Destruction on an Annual Basis
43	TurbnEngine	4.85%	211	2.80%
44	OtherMach	4.85%	211	2.80%
45	Computers	6.21%	266	4.53%
46	CmptrStorage	6.21%	266	4.53%
47	ComptrTrmEtc	6.21%	266	4.53%
48	CommunicEqp	4.81%	211	2.78%
49	MscElctEqp	4.81%	211	2.78%
50	Semicondctr	4.81%	211	2.78%
51	ElecInstrmnt	4.81%	211	2.78%
52	HholdEqp	4.81%	211	2.78%
53	MVPManu	4.85%	211	2.80%
54	AerospaceMan	4.85%	211	2.80%
55	RlrdCars	4.85%	211	2.80%
56	ShipsBoats	4.85%	211	2.80%
57	OthTrnEqp	4.85%	211	2.80%
58	Furniture	4.81%	211	2.78%
59	MiscManuf	4.81%	211	2.78%
60	WholesaleTr	4.68%	217	2.78%
61	AirTrans	4.09%	251	2.81%
62	RailTrans	4.09%	251	2.81%
63	WaterTrans	4.09%	251	2.81%
64	TruckTrans	4.68%	217	2.78%
65	GrdPassTrans	4.09%	251	2.81%
66	Pipeline	4.09%	251	2.81%
67	OthTransprt	4.85%	211	2.80%
68	Warehousing	4.68%	217	2.78%
69	RetailTr	4.22%	217	2.51%
70	Publishing	4.81%	211	2.78%
71	MovieSound	4.09%	251	2.81%
72	BroadcastSrv	4.51%	186	2.30%
73	Telecomm	4.51%	186	2.30%
74	InfoSvce	4.09%	251	2.81%
75	DataProcScv	4.09%	251	2.81%
76	FinancBank	3.92%	219	2.36%
77	RealEstate	4.09%	251	2.81%
78	RentLease	4.09%	251	2.81%
79	AssetLessors	4.09%	251	2.81%
80	PrfSciTchSrv	4.09%	251	2.81%
81	WasteMgmt	4.54%	259	3.22%

TERM Sector #	Short names	% Building & Content Loss	Average Recovery Time (Days)	% Capital Input Destruction on an Annual Basis
82	Education	3.12%	223	1.91%
83	HealthSocAs	3.91%	249	2.63%
84	ArtsRecreat	4.51%	186	2.30%
85	Accommodatn	3.47%	247	2.35%
86	EatDrinkPlce	4.51%	186	2.30%
87	OthService	4.07%	217	2.42%
88	GovEnterprs	4.07%	217	2.42%
89	StaLocGov	4.54%	259	3.22%
90	OwnOccDwell	4.08%	238	2.69%
91	FedGovt	4.08%	238	2.69%
92	Holiday	4.51%	186	2.30%
93	FgnHol	4.51%	186	2.30%
94	ExpTour	4.51%	186	2.30%
95	ExpEdu	3.12%	223	1.91%
96	WT_EXP	4.09%	251	2.81%
97	AT_EXP	4.09%	251	2.81%

7. Socioeconomic Impacts of the Simulated Earthquake Scenario

7.1. Aggregate Impacts of Port Disruptions

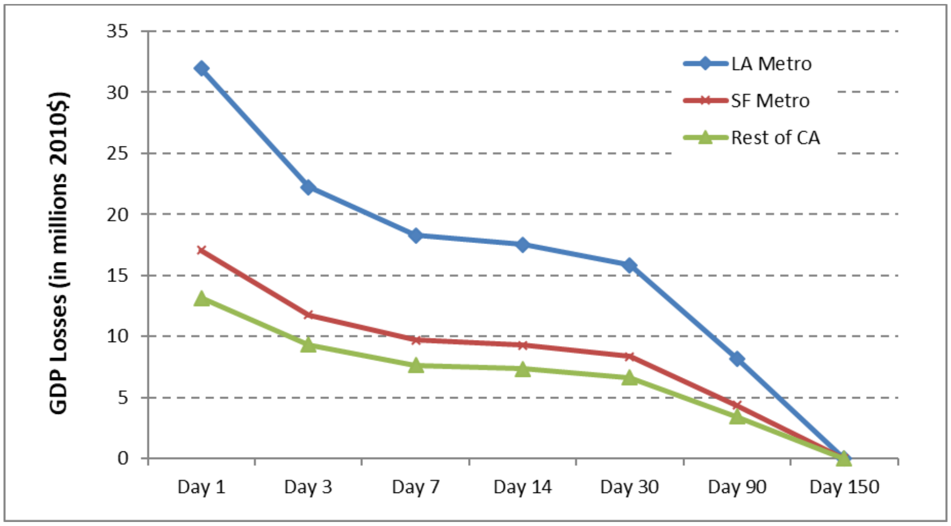
To simulate the macroeconomic impacts of port disruptions, we first translated reductions in port functionality into disruptions of import and export flows through the twin ports. We further calculated the percentage reductions in import uses and export production by sector in each of the TERM regions. In the TERM Model, the import disruption was implemented through a shock of the import price (fimps) variable while the disruption of export was implemented through a shock of the export quantity (fqexp) variable.

Table 18 presents the gross domestic product (GDP) impacts of the port disruptions for the seven key days over the recovery path. The last row of Table 18 presents the total GDP losses over the entire recovery period of 150 days. The GDP impacts are interpolated between any two key days based on the assumption of linear recovery (as illustrated in Figure 11 for sub-regions in California). For the LA Metro Region, we estimate that the port disruptions caused by the simulated earthquake scenario would result in a $1.51 billion loss in GDP, or a 0.219% reduction. The other regions in California as well as Rest of U.S. also experience GDP losses, but in smaller magnitudes in percentage terms because LA Region is the direct recipient and direct user of nearly 50% of the import shipments through Ports of Los Angeles and Long Beach (for inputs into production and final demand). The total GDP losses for the U.S. as a whole is about $9.4 billion, though this is only less than a one-tenth of one percent decline at this level.

Table 18. Real GDP Impacts of Port Disruptions
(million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	Rest of US	US Total
Day 1	-32.0 -0.0046%	-17.1 -0.0042%	-13.2 -0.0027%	-141.7 -0.0013%	-203.9 -0.0016%
Day 3	-22.2 -0.0032%	-11.8 -0.0029%	-9.3 -0.0019%	-94.5 -0.0009%	-137.8 -0.0011%
Day 7	-18.3 -0.0026%	-9.7 -0.0024%	-7.7 -0.0016%	-76.9 -0.0007%	-112.5 -0.0009%
Day 14	-17.5 -0.0025%	-9.3 -0.0023%	-7.4 -0.0015%	-74.0 -0.0007%	-108.2 -0.0009%
Day 30	-15.8 -0.0023%	-8.4 -0.0021%	-6.6 -0.0014%	-66.6 -0.0006%	-97.4 -0.0008%
Day 90	-8.2 -0.0012%	-4.4 -0.0011%	-3.4 -0.0007%	-35.8 -0.0003%	-51.7 -0.0004%
Day 150	0.0 0%	0.0 0%	0.0 0%	0.0 0%	0.0 0%
Total	-1,508.8 -0.2187%	-800.9 -0.1971%	-632.6 -0.1311%	-6,446.2 -0.0590%	-9,388.4 -0.0759%

Figure 11. GDP Losses on Key Days after the Earthquake Event



Like other CGE models, the TERM Model automatically takes into consideration three types of inherent economic resilience that work through the price system. These include input substitution, import substitution, and regional production shifts (IIR).[15] Following the methodology developed in Wei et al. (2020), we estimate the loss reduction potential of the IIR by comparing the simulation results using the input-output (I-O) analysis and the TERM simulation results of the port disruptions. The I-O analysis is based on the assumption of fixed production coefficients (or a linear relationship between the changes in production inputs and changes in the output), and thus can be used as the Base Case with no resilience tactics incorporated. Table 19 first presents the GDP impacts of the Base Case (no resilience) and the GDP impacts obtained from the TERM simulations that take into consideration the three major types of inherent resilience tactics (IIR). The last two columns in Table 19 present the loss reduction potential for the resilience tactics in percentage terms. A comparison of the results from the TERM Model (second row) and the I-O analysis (first row) indicates that the inherent economic resilience estimated by the TERM CGE Model (input substitution, import substitution, and production activity relocation) reduces the potential GDP losses by 87.2% for the LA Metro Region. At the national level, the loss reduction potentials are 86.1%.

We next run a simulation, in which we take into consideration the various resilience tactics pertaining to port disruptions summarized in Table 2. Table 20 summarizes the analytical approach we use to simulate the effects of these resilience tactics in the TERM Model. Column 1 of the table lists the various resilience tactics. More details of the modeling approach are presented in the next two columns. The results are presented in the last row of Table 19. The combined resilience can reduce GDP losses from $11.8 billion to $0.24 billion for the LA Metro Region and from $67.5 billion to $0.65 billion for the U.S., or a reduction of GDP losses by about 97.9% for the LA Metro Region and over 99% for the U.S. compared to the Base Case. Note that the effects of the various resilience tactics are not additive because of overlaps in their application.

Table 19. Real GDP Impact of Port Disruptions – Base Case and Resilience Cases (million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (no resilience)	-11,766.40 -1.71%	-5,057.80 -1.24%	-5,425.40 -1.12%	-45,252.80 -0.41%	-67,502.50 -0.54%		
With Inherent Resilience (IIR)	-1,508.82 -0.22%	-800.85 -0.20%	-632.62 -0.13%	-6,446.15 -0.06%	-9,388.44 -0.08%	87.18%	86.09%
With Combined Resilience (IIR, Other Inherent, Adaptive Resilience)	-243.73 -0.04%	-54.80 -0.01%	-66.05 -0.01%	-283.97 0.00%	-648.55 -0.01%	97.93%	99.04%

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[15] Input substitution refers to utilizing similar goods in the production process to those whose production has been disrupted (again both directly and indirectly). Import substitution refers to bringing in goods and services in short supply from outside the region through transportation means other than water transportation. Regional production shift refers to shifting production to branch plants or losing production opportunities to competitors in other locations.

Table 20. Modeling Tactics for Economic Resilience in the TERM Model

	Simulation Method	**Description**	**Adjustment Level or Range for Base Case Resilience**
Conservation	Adaptive resilience is captured by adjusting import and export shocks in different regions	Utilize less of disrupted imported goods in production processes.	Adjust import and export shocks by 2% in all regions
Inherent Input Substitution	N/A	Inherent input substitution is captured by the CGE model automatically.	N/A
Import Substitution	N/A	Inherent import substitution is captured by the CGE model automatically by the Armington elasticity of substitution.	N/A
Ship Rerouting	Adjust import and export shocks in different regions	Steering ships to other nearby ports.	Reduce Base Case import and export shocks by 50% across sectors
Effective Management	Adjust import and export shocks	Improvements in decision-making and expertise that enhance functionality (e.g., information sharing, utilizing digital incoming cargo shipment data to increase cargo handling productivity).	Reduce Base Case import shocks by 10% across sectors
Export Diversion for Import Use	Adjust import and export shocks	Using goods that were intended for export as substitutions for the lack of availability of imports.	Reduce import and export disruptions between 0% and 100% across sectors (depending on availability of similar 10-digit HTS exported commodity that can be sequestered for import use)
Inventory Use	Adjust import shock	Reducing the direct import disruption by the amount of inventory.	Reduce import disruptions between 0% and100% across sectors (based on a comparison of BEA inventory data and Base Case import disruptions by sector)
Production Recapture	Application of “Recapture Factor Parameter” to output changes	A side-calculation to adjust total output losses for production rescheduling.	Recapture factors range from 0.223 to 0.429 across sectors.

7.2. Aggregate Impacts of Truck Transportation Cost Increases

Table 13 presents the percentage increase in transportation cost both within the LA Metro Region and between LA Metro Region and Rest of CA period by period over the entire recovery timeframe. Since the simulations in the TERM Model are conducted on an annual basis, we first translated the transportation cost increases over the 104-day period presented in Table 13 to an overall percentage transportation cost increase on a yearly basis. This is calculated as a 0.5271% increase in truck transportation cost within the LA Metro Region and a 0.26356% increase between the LA Metro Region and Rest of CA (on an annual basis).

In the TERM Model, transportation cost is treated as part of the trade margin, which is added to the price of final commodities. The model enables us to implement a shock of trade margin through an adjustment of the technical efficiency parameter of margin usage (variable "atradmar_cs(m,r,d)"), which represents the number of units of margin, *m*, required to facilitate transactions of goods going from region *r* to region *d*. The regional economic impacts of the increased transportation costs are estimated through the following five shocks simultaneously: margin increases of trucks from LA to LA, from LA to Rest of CA, from Rest of CA to LA, from LA to SF, and from SF to LA.

Table 21 presents the GDP impacts of transportation cost increases in both dollar values and percentage terms for various regions. The GDP losses in the LA Metro Region are estimated to be $14.5 million. Rest of California will only experience very slight GDP losses. Rest of US is estimated to have a small increase in GDP of $3.60 million, which can be explained by the effect of regional production shifts automatically captured by the TERM Model that are caused by a truck transportation cost increase (and thus an implicitly production cost increase) in the LA Metro Region and Rest of CA in comparison to Rest of US. The resilience tactic of a more rapid opening of critical highway corridors during the first week after the seismic event is estimated to have a loss reduction potential of about 10% over the entire recovery period.

Table 21. Real GDP Impact of Truck Transportation Cost Increase (million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (no resilience)	-14.54 -0.00211%	0.09 0.00002%	-0.68 -0.00014%	3.60 0.00003%	-11.53 -0.00010%		
Resilience Case	-13.15 -0.00191%	0.08 0.00002%	-0.62 -0.00013%	3.28 0.00003%	-10.41 -0.00009%	9.54%	9.66%

7.3. Aggregate Impacts of General Building Stock Damages

The simulated earthquake also results in destructions and damages to general building stock in the Los Angeles metropolitan region, which in turn result in interruptions to the flow of goods and services emanating from the productive capital stock. The total economic impacts resulting from the capital stock damages are simulated by shocking the variable "xcap" (physical capital supply) by industry by region in the TERM Model using the HAZUS results on percentage of building and content losses presented in the last column of Table 16.

Table 22 first presents the GDP impacts of general building stock damages for the Base Case, in which no resilience is considered. The total GDP losses are estimated to be nearly $20 billion in the LA Metro

Region, or a 2.8% reduction from the baseline level on an annual basis. The Rest of CA (excluding Northern California) is estimated to experience very slight GDP losses. The Rest of the U.S. is estimated to have an increase in GDP of $2.8 billion, which can be explained by the effect of regional production shifts or locational substitution of economic activities automatically captured by the TERM Model when the LA Metro Region is shocked by the simulated disaster.

Table 22 also presents the results of a simulation in which we take into consideration two major resilience tactics to general building stock damages. One is the use of undamaged spare/excess capacity by the producing sectors to maintain certain level of production and the other is production recapture, which refers to working overtime or extra shifts after the producing sectors have repaired or replaced the necessary equipment and their employees and critical inputs become accessible.[16] The analysis results indicate that the combined effects of these two resilience tactics can reduce GDP losses from $19.2 billion to $11.8 billion for the LA Metro Region and from $16.5 billion to $10.1 billion for the U.S. as a whole, or a reduction of GDP losses by about 38% compared to the Base Case.

Table 22. Real GDP Impact of General Building Damages – Base Case and Resilience Cases (million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (no resilience)	-19,223.06 -2.79%	93.20 0.02%	-98.73 -0.02%	2,757.50 0.03%	-16,471.08 -0.14%		
Combined Resilience Case	-11,843.32 -1.72%	58.24 0.01%	-60.71 -0.01%	1,696.60 0.02%	-10,149.19 -0.09%	38.39%	38.38%

When we compare the economic impacts of the three types of disruptions/damages we simulated for the earthquake scenario -- port disruption, hinterland transportation cost increase, and general building damages, the impacts from general building damages account for over 92% of the total impacts in the LA Metro Region before resilience other than IIR is taken into account. The hinterland transportation system disruption results in the smallest impacts because of the high redundancy of the transportation network in the region. It is estimated that the intra-regional percentage increase in transportation cost can be greatly reduced from about 10% right after the strike of the earthquake to 1.3% in one-week time. For the U.S. as a whole, impacts from general building damages account for about 63% of the total impacts (without resilience adjustments), while the port disruptions account for another one third of the total impacts. When we take the effects of the various resilience tactics into consideration,

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[16] We adapt the recapture factors from HAZUS, the FEMA loss and risk assessment software for disasters (FEMA, 2013). Since the HAZUS recapture factors pertain to the maximum potential recapture capability, in the analysis we cut the recapture percentages in half in order to account for obstacles to implementation. Furthermore, we assume that the recapture factors are reduced by 25 percent for each three-month period within a year. Thus, after the first year, there is no production recapture.

impacts from general building damages account for nearly 98% of the total impacts in the LA Metro Region and 94% for the U.S. This is because there are more effective resilience tactics on both the supplier-side and customer-side the businesses can implement to deal with port disruptions and supply chain shortages than with physical damages to buildings and facilities, and therefore the impacts from port disruptions in the combine resilience case are greatly muted.

7.4. Combined Economic Impacts

After we analyze the economic impacts for each of the three disruption types (port disruption, hinterland transportation cost increase, and general building damages) individually, we also run a simulation in which we combine all three types of disruptions/damages together. This simulation is run for both the Base Case and the Combined Resilience Case. The GDP impacts for each region are presented in Table 23. The total GDP losses are estimated to be $20.7 billion (or a 3% reduction) in the LA Metro Region, and $25.8 billion in the U.S. as a whole (or a 0.21% reduction). The various resilience tactics can help reduce the total impacts to $12.1 billion in the LA Metro Region, or a loss reduction of 41.3%, and reduce the total impacts for the U.S. as a whole to $11 billion, or a loss reduction of 57.6%. The reason that the total impacts on the U.S. as a whole are less than the total impacts on the LA Metro Region in the Combined Resilience Case is because the Rest of U.S. is expected to experience an overall increase in economic activities because of the regional production shifts after the earthquake hits the Los Angeles area.

Table 23. Real GDP Impact of the Combined Disruptions/Damages– Base Case and Resilience Cases (million 2010 $ and percent reduction from pre-disaster levels)

	LA Metro	SF Metro	Rest of CA	Rest of US	US Total	Loss Reduction Potential (for LA)	Loss Reduction Potential (for US)
Base Case (no resilience)	-20,707.99	-708.04	-731.81	-3,674.78	-25,822.62		
	-3.00%	-0.17%	-0.15%	-0.03%	-0.22%		
Combined Resilience Case	-12,147.43	-10.02	-142.66	1,343.86	-10,956.25	41.34%	57.57%
	-1.76%	0.00%	-0.03%	0.01%	-0.09%		

7.5. Income Distribution Impacts

Based on the simulation results obtained from the TERM Model, we performed income distribution analyses for the LA Metro Region (the most affected region by the simulated earthquake scenario) using the following steps:

1. Obtain baseline labor income by sector from the TERM Model.
2. Scale up the baseline labor income to obtain total personal income by sector using the labor income to capital income ratios from the Multi-Sector Income Distribution Matrix (MSIDM) calculations (see Section 4.3. for details).

3. Apply the percentage effective labor input changes by sector obtained from the TERM simulations to the baseline personal income calculated in Step 2 to obtain the changes in personal income by sector.
4. Multiply the changes in personal income in each sector by the MSIDM to determine the profile of income changes by bracket associated with different disruption/damage types individually and combined. The results are summed across sectors to obtain an overall change in income distribution of the economy as a result of the shock.
5. Calculate the Gini coefficients for the various disruption simulations. The Gini coefficient is a one-parameter estimate of the skewness of the income distribution by comparing the Lorenz curve with the perfect equality line. The coefficient ranges from 0 to 1, with 0 representing perfect equality and 1 representing perfect inequality.

Tables 24 to 27 present the income distribution impacts for the port disruption case, transportation cost increase case, general building damage case, and the three cases combined, respectively. The tables first present the distribution of personal income across income brackets in the baseline, then followed by the income distribution impacts for both post-disruption simulation cases (Base Case and Combined Resilience Case). For port disruptions, the percentage reduction in income are relatively higher for the lower- to middle-income groups in the Base Case, but are relatively higher for the middle- to high-income groups in the Combined Resilience Case. For the transportation cost increase simulation, the percentage changes are relatively higher for some middle- and upper-income groups, meaning that these groups bear a relatively greater proportion of the income losses due to the transportation costs increase. For the building damage simulations, the middle- and higher-income groups in general experience relatively higher income losses in both the Base Case and Resilience Case. This can be explained by the fact that a higher proportion of capital-related income is earned by higher-income groups.

Table 28 first presents the Gini coefficients for the income distribution in the baseline and in the various simulation cases. The changes in Gini coefficient relative to the baseline level are presented in the second to last column. Finally, we compute the Gini coefficient for the income loss alone in the last column. The Gini coefficient is higher than in the baseline for the port disruption Base Case, which indicates that the disruption is born slightly disproportionately by lower- and middle-income groups. The Resilience Case results in a Gini coefficient that is slightly lower than the baseline level, which is explained by the fact that the various resilience tactics are more effective in reducing the impacts in the sectors that employ more people from the lower-income groups. The Gini coefficients of the other cases decrease compared to the baseline level, which indicates that the income losses stemming from transportation cost income and general building damages are born disproportionately by middle- and higher-income groups. Since the impacts of general building damages account for over 90% of the total impacts in the LA Metro Region, the combined simulation of all three types of disruptions/damages also yields lower Gini coefficients than in the baseline.

Table 24. Baseline Income Distribution and Income Changes in the Port Disruption Simulation for the LA Metro Region (million 2010$)

Income Bracket	Income Distribution			Income Changes relative to Baseline (M $)		Income Changes relative to Baseline (%)	
	Baseline	Port Disruption Base Case	Port Disruption Resilience Case	Port Disruption Base Case	Port Disruption Resilience Case	Port Disruption Base Case	Port Disruption Resilience Case
<10k	3,474.1	3,470.5	3,472.2	-3.64	-1.87	-0.1048%	-0.0539%
10-15k	9,993.2	9,981.3	9,987.6	-11.96	-5.58	-0.1196%	-0.0558%
15-25k	20,527.7	20,461.1	20,511.8	-66.55	-15.90	-0.3242%	-0.0775%
25-35k	37,426.9	37,290.4	37,392.5	-136.49	-34.40	-0.3647%	-0.0919%
35-50k	56,675.1	56,495.4	56,620.7	-179.67	-54.38	-0.3170%	-0.0960%
50-75k	77,908.2	77,686.9	77,838.1	-221.32	-70.11	-0.2841%	-0.0900%
75-100k	74,636.7	74,459.5	74,573.8	-177.17	-62.89	-0.2374%	-0.0843%
100-150k	80,606.5	80,413.0	80,541.8	-193.49	-64.71	-0.2400%	-0.0803%
150k+	164,409.6	164,042.7	164,261.3	-366.88	-148.22	-0.2231%	-0.0902%
Total	525,658.0	524,300.8	525,199.9	-1,357.16	-458.05	-0.2582%	-0.0871%

Table 25. Baseline Income Distribution and Income Changes in the Transportation Cost Increase Simulation for the LA Metro Region (million 2010$)

Income Bracket	Income Distribution			Income Changes relative to Baseline (M $)		Income Changes relative to Baseline (%)	
	Baseline	Transportation Cost Increase Base Case	Transportation Cost Increase Resilience Case	Transportation Cost Increase Base Case	Transportation Cost Increase Resilience Case	Transportation Cost Increase Base Case	Transportation Cost Increase Resilience Case
<10k	3,474.1	3,474.1	3,474.1	-0.05	-0.05	-0.0015%	-0.0013%
10-15k	9,993.2	9,993.1	9,993.1	-0.14	-0.13	-0.0014%	-0.0013%
15-25k	20,527.7	20,527.3	20,527.3	-0.43	-0.38	-0.0021%	-0.0019%
25-35k	37,426.9	37,426.1	37,426.2	-0.80	-0.72	-0.0021%	-0.0019%
35-50k	56,675.1	56,674.0	56,674.1	-1.14	-1.03	-0.0020%	-0.0018%
50-75k	77,908.2	77,907.0	77,907.1	-1.25	-1.13	-0.0016%	-0.0014%
75-100k	74,636.7	74,635.1	74,635.3	-1.53	-1.39	-0.0021%	-0.0019%
100-150k	80,606.5	80,604.9	80,605.0	-1.56	-1.41	-0.0019%	-0.0017%
150k+	164,409.6	164,405.9	164,406.3	-3.66	-3.31	-0.0022%	-0.0020%
Total	525,658.0	525,647.4	525,648.4	-10.55	-9.55	-0.0020%	-0.0018%

Table 26. Baseline Income Distribution and Income Changes in the General Building Damages Simulation for the LA Metro Region (million 2010$)

Income Bracket	Income Distribution			Income Changes relative to Baseline (M $)		Income Changes relative to Baseline (%)	
	Baseline	Building Damage Base Case	Building Damage Resilience Case	Building Damage Base Case	Building Damage Resilience Case	Building Damage Base Case	Building Damage Resilience Case
<10k	3,474.1	3,377.9	3,398.4	-96.20	-75.67	-2.7691%	-2.1780%
10-15k	9,993.2	9,717.5	9,776.4	-275.76	-216.84	-2.7595%	-2.1699%
15-25k	20,527.7	19,961.7	20,083.6	-566.02	-444.08	-2.7573%	-2.1633%
25-35k	37,426.9	36,265.9	36,516.9	-1,161.03	-910.02	-3.1021%	-2.4314%
35-50k	56,675.1	54,770.7	55,181.9	-1,904.45	-1,493.25	-3.3603%	-2.6347%
50-75k	77,908.2	75,260.2	75,831.4	-2,648.01	-2,076.80	-3.3989%	-2.6657%
75-100k	74,636.7	71,997.2	72,564.3	-2,639.49	-2,072.35	-3.5365%	-2.7766%
100-150k	80,606.5	77,818.8	78,417.5	-2,787.64	-2,188.98	-3.4583%	-2.7156%
150k+	164,409.6	157,795.0	159,211.6	-6,614.55	-5,197.95	-4.0232%	-3.1616%
Total	525,658.0	506,964.8	510,982.0	-18,693.14	-14,675.92	-3.5561%	-2.7919%

Table 27. Baseline Income Distribution and Income Changes in the Combined Disruptions/Damages Simulations for the LA Metro Region (million 2010$)

Income Bracket	Income Distribution			Income Changes relative to Baseline (M $)		Income Changes relative to Baseline (%)	
	Baseline	Combined Simulation Base Case	Combined Simulation Resilience Case	Combined Simulation Base Case	Combined Simulation Resilience Case	Combined Simulation Base Case	Combined Simulation Resilience Case
<10k	3,474.1	3,374.3	3,396.6	-99.81	-77.52	-2.8729%	-2.2313%
10-15k	9,993.2	9,705.6	9,770.9	-287.58	-222.35	-2.8778%	-2.2250%
15-25k	20,527.7	19,895.6	20,067.7	-632.10	-460.04	-3.0792%	-2.2411%
25-35k	37,426.9	36,130.8	36,482.5	-1,296.16	-944.39	-3.4632%	-2.5233%
35-50k	56,675.1	54,593.2	55,127.9	-2,081.94	-1,547.22	-3.6735%	-2.7300%
50-75k	77,908.2	75,043.0	75,762.3	-2,865.25	-2,145.98	-3.6777%	-2.7545%
75-100k	74,636.7	71,822.9	72,502.2	-2,813.79	-2,134.48	-3.7700%	-2.8598%
100-150k	80,606.5	77,629.4	78,353.6	-2,977.10	-2,252.84	-3.6934%	-2.7949%
150k+	164,409.6	157,432.8	159,065.7	-6,976.73	-5,343.91	-4.2435%	-3.2504%
Total	525,658.0	505,627.5	510,529.2	-20,030.47	-15,128.73	-3.8106%	-2.8781%

Table 28. Gini Coefficient Impacts

Disruption Type	Baseline	Scenario Gini Coefficient	Change in Gini Coefficient	Gini Coefficient of the Income Loss
Port Disruption_Base Case	0.465478	0.465614	0.000136	0.413109
Transportation Cost Increase_Base Case	0.465478	0.465478	0.000000	0.490154
Building Damage_Base Case	0.465478	0.463904	-0.001574	0.508171
Combined Disruptions_Base Case	0.465478	0.464041	-0.001438	0.501768
Port Disruption_Resilience Case	0.465478	0.465473	-0.000006	0.471813
Transportation Cost Increase_Resilience Case	0.465478	0.465478	0.000000	0.490157
Building Damage_Resilience Case	0.465478	0.464243	-0.001235	0.508481
Combined Disruptions_Resilience Case	0.465478	0.464238	-0.001240	0.507328

8. Conclusion

In this study, we contribute to the economic impact analysis of ports and their hinterland transportation infrastructure disruptions in two dimensions. First, we developed an integrated model that links a transportation network model with an economic impact analysis model in order to conduct a more holistic and accurate analysis of the impacts of and resilience to the transportation system disruptions. Second, to fill in an important gap in the port and transportation network disruption literature, we examine not only the impacts of such disruptions and the effectiveness of resilience tactics at the aggregate level, but also the income distribution impacts across socioeconomic groups. As a case study, the integrated model is applied to a simulated earthquake scenario that affects commodity trade flows at the Port of Los Angeles and Port of Long Beach and their associated inland highway freight transportation network.

The results indicate that it takes 150 days for the ports to fully recover from the simulated seismic event. The total GDP impacts stemming from both import and export disruptions are estimated to be $11.8 billion in the LA Metro Region and $67.5 billion for the U.S. before we consider any resilience. These impacts are reduced to $1.5 billion in the LA Metro Region and $9.4 billion for the U.S. after we take into consideration three major types of inherent economic resilience (input substitution, import substitution, and regional production shifts) that are automatically captured by the TERM CGE Model. After we consider the other types of inherent resilience tactics and adaptive resilience tactics, the total impacts are further reduced to $0.24 billion in the LA Metro Region and $0.65 billion in the U.S. In addition, the damage to the highway transportation system also causes a 0.53% increase in truck transportation cost within the LA Metro Region and a 0.26% increase between LA Metro Region and Rest of CA (on an annual basis). The estimated GDP losses caused by the truck transportation cost increases are only $15 million in the LA Metro Region because of the high redundancy of the transportation network. The simulated seismic events also result in damages to the general building stock. The total GDP losses are estimated to be $19.2 billion in the LA Metro Region, which is reduced to $11.8 billion after the adjustment for resilience. The GDP losses for the U.S. are $16.5 billion with no resilience, and $10.1 billion after the resilience adjustments. The lower impacts at the national level are due to the offsetting effect stemming from regional production shifts from the earthquake impacted region to other regions in the country. The combined simulation of all three types of disruptions/damages yields GDP losses of $12.1 billion for the LA Metro Region and $10.9 billion for the U.S. after we consider all the relevant resilience tactics. The loss reduction potential of resilience is 41.3% at the regional level of LA and 57.6% at the national level.

The income distribution analyses for the LA Metro Region indicate that the income losses stemming from port disruptions are born slightly disproportionately by lower- and middle-income groups. The Resilience Case for port disruptions results in a Gini coefficient that is slightly lower than the baseline level (indicating a more equitable distribution of income), which is explained by the fact that the various resilience tactics are more effective to reduce the impacts in the sectors that employ more people from the lower-income groups. The Gini coefficients of the other cases decrease compared to the baseline level, which indicates that the income losses stemming from transportation cost income and general building damages are born disproportionately by middle- and higher-income groups. Since the impacts of general building damages account for over 90% of the total impacts in the LA Metro Region, the combined simulation of all three types of disruptions/damages also yield lower Gini coefficients (or a more equitable distribution of income) than in the baseline. This can be explained by the fact that a higher proportion of capital-related income is earned by higher-income groups. Therefore, these income groups are expected to experience a higher proportion of income losses from capital stock damages.

The authors also investigated adaptive resilience tactics relating to the transportation system (consisting of port and road network supply, and travel demand) and the corresponding improvements in functionality losses due to the initial disruption. In Table 2, such tactics are categorically mentioned as *effective road (port) infrastructure asset management* which includes improvements in decision making that allocates resources for expedited repair and reconstruction. To demonstrate the capabilities of the coupled model for such tactics, the authors conducted simulations trying to quantify the benefits of rapidly opening critical corridors in the hinterland road network to service. Specifically for the case study for the Ports of LA and LB, these critical corridors could be freeways that link the port complex to the 405 Freeway and beyond (110 and 710). The I405 corridor between I10 and I110 was identified as a critical corridor that could be kept open (See Section 6.1.2.) due to the relatively lower levels of estimated damage in 8 bridges away from the epicenter of the scenario earthquake. This adaptive resilience tactic was shown to mitigate a significant amount (about 25%) of system functionality loss in Days 1 to 7 after the seismic event as illustrated by Figure 10, corresponding to 220,000 hours of improvement in VHT in the study region. Such calculations can provide important insights for decision-makers, particularly for asset management and strategic recovery actions after natural hazards. The research framework presented in this report could be deployed for such purposes, as well as other events causing closures in the system (e.g., acts of terrorism, traffic accidents, etc.). A similar analysis could be done for the port infrastructure. The challenge here is the general lack of data on the capabilities of asset owners and managers to expedite the repair and reconstruction efforts.

With regard to modeling the post disaster travel behavior to advance the deployment of the coupled model beyond the fixed (post-disaster) travel demand assumption made in this study, the authors have two options in their future work. The first is to make assumptions on behavioral responses such as the stay-at-home (telecommuting) behavior due to reduced network functionality. This also relates to a mentioned resilience tactic in Table 2 (effective travel demand management). 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 recovery of functionality 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 the travel demand model. Most destination choice and mode choice models are based on utility theory with utility functions accommodating terms for travel distance and time parameters (SCAG, 2019). 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 to note that these results will always be prone to a lack of validation against empirical data. Khademi et al. (2015) identify the work of Nagae et al. (2012) 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. (2012) 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. 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. In consideration of these issues, post-disaster travel demand investigations will be carried out in the authors' future work.

We also note the important difference between potential resilience and actual resilience. The existence of various coping measures we modeled in this study does not mean they will be optimally used given the likelihood of restrictive regulations, bounded rationality, and market failures. Our study estimates the loss reduction effects of only potential resilience. However, our analysis provides insights to port managers and operators, businesses that rely on operations of the ports and the freight transportation network, and policy makers to identify and implement these powerful resilience tactics and enhance business contingency and continuity planning to cope with seaport and transportation network disruptions as targets for their decisions.

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Data Management Plan

Products of Research

For the transportation model, SCAG's regional travel model with 2016 data was adopted from the regional MPO. The model is based on extensive socioeconomic and travel data as well as a high resolution network dataset. Details on the SCAG Model are available in model documentation (SCAG 2019).

Earthquake scenario and associated data were generated in a parallel study involving a collaboration with the Taciroglu Research Group at UCLA (Koc et al., 2020). A map showing the epicenter of the scenario earthquake event, the component of the Palos Verdes connected fault system, and the bridges that are closed due to damage on Day 1 after the strike of the earthquake is shared (see details below).

Another set of maps are shared for the transportation simulation results for Days 1-30 where regional mobility is estimated to experience a major disruption. These include vehicle flow and VMT maps, respectively.

The data used in the construction of the MSIDM of California are summarized in detail in Chapter 4.3 in the report. The major components of the MSIDM, including the distribution matrices of Employee Compensation, Proprietors' Income, Dividend and Other Property Income, and Personal Transfer Receipts are presented in Appendix C.

Data Format and Content

The transportation system and disaster simulation data are shared in the format of ArcGIS online maps.

Data Access and Sharing

The maps generated as results of this study are listed below, including links of the websites where they are hosted indicated in the footnotes:

1. Bridge Closures on Day 1 after the Scenario Earthquake: Closed bridges on Day 1 based on hybrid (image-to-model + HAZUS) inventory. Map also shows epicenter of the event and the Palos Verdes fault as well as the SCAG RTDM network model.[17]
2. Days 1-7 AM Vehicle Flow: Percent change in vehicle flow in Days 1-7 with respect to Day 0 (pre-disaster baseline). Results for AM Peak.[18]
3. Days 7-30 AM Vehicle Flow: Percent change in vehicle flow in Days 7-30 with respect to Day 0 (pre-disaster baseline). Results are for AM Peak.[19]
4. Days 1-7 AM VMT: Percent change in VMT in Days 1-7 with respect to Day 0 (pre-disaster baseline). Results for AM Peak and are summarized at TAZ level-of-detail.[20]

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[17] Bridge Closures on Day 1 after Scenario Earthquake. Access online at https://arcg.is/T9vyb
[18] Days 1-7 AM Vehicle Flow: Access online at https://arcg.is/0SabHn
[19] Days 7-30 AM Vehicle Flow: Access online at https://arcg.is/111qmm
[20] Days 1-7 AM VMT: Access online at https://arcg.is/1Gz4Wm

5. Days 7-30 AM VMT: Percent change in VMT in Days 7-30 with respect to Day 0 (pre-disaster baseline). Results for AM Peak and are summarized at the TAZ level-of-detail.[21]

Reuse and Redistribution

The shared maps are for viewing purposes only due to the data sharing agreements between the authors and the providers. Readers may contact the project team for access to the data and other collaboration opportunities.

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[21] Days 7-30 AM VMT: Access online at https://arcg.is/1q8ref

Appendix A. Port Optimizer at POLA/POLB

Port Optimizer at POLA/POLB

Port Optimizer is a cloud-based software solution developed by General Electric (GE) Transportation, a unit of Wabtec Corp, in partnership with the Port of Los Angeles. The tool generates data-driven insights to maximize port throughput and delivery performance. It integrates data from across the port ecosystem—including inbound containers and aspects of port operations—into a single portal that partners across the supply chain can access (GE Transportation, 2018a). More broadly, Port Optimizer is part of the fourth wave of port community systems, a class of software products that connect port actors (Moros-Daza, Amaya-Mier, & Paternina-Arboleda, 2020).

GE Transportation first launched the tool in November 2016 as a two-month pilot at the Port of Los Angeles (Ames, 2016). Port executives deemed the test a success and signed a $12 million, five-year contract the following year (Ames, 2018). In March 2018, GE Transportation announced it would expand Port Optimizer to all terminals and shipping lines at the Port of Los Angeles, and also launch a pilot at Long Beach. The trial concluded in October 2018, but the Port of Long Beach has not yet permanently adopted Port Optimizer.

As of March 2019, Port Optimizers handled data from nine of the top 11 shipping lines operating through the Port of Los Angeles and the Port of Long Beach (DC Velocity, 2019). By December 2019, data on 95% of all inbound cargo was seen by Port Optimizer (Tirschwell, 2019). The Port provides financial incentives for shipping lines that share data through the Port Optimizer, and that can prove above-average cargo growth (Maschke, 2019). Nevertheless, some terminal operators, beneficial cargo owners, equipment providers, and other stakeholders are reluctant to share company data (Mongelluzzo, 2019b).

Quantitative assessment of efficiency improvements

Port Optimizer promotional materials suggest that Port Optimizer can increase productivity by 8-12% “as the solution scales” (GE Transportation, 2018a). The pilot at the Port of Long Beach reportedly resulted in 14+ days faster access to information on incoming cargo (GE Transportation, 2018b).

Gene Seroka, executive director of the Port of Los Angeles, told the Board of Harbor Commissioners that the Port could repay its investment in the tool if its business grew by 2% through efficiency gains (Port of Long Beach, 2018).

Terminal operators and truckers see the potential for the tool to improve visibility and cargo velocity, but one terminal operator has said they “haven’t seen any improvement” (Mongelluzzo, 2019a). A GE Transportation director has said it is too soon for data on results.

Port Optimizer and emergency events

Promotional materials and news coverage do not explicitly discuss Port Optimizer in the context of emergency events such as disruptions due to natural disasters. Tijan, Kos, and Ogrizović (2009) detail how port executives can ensure that port community systems continue to function in case of a disaster. They note that cooperation between those operating the system and customers on disaster recovery plan execution and maintenance cost sharing can be money-saving.

Appendix B. TERM CGE Model Sectoring Scheme

Appendix Table B. TERM CGE Model Sectoring Scheme

TERM Sector	Short names	Description	Bridging to IMPLAN Sectors
1	Crops	Crops	1-10
2	PoultryEggs	Poultry & Eggs	13
3	Livestock	Livestock	11-12
4	OthLivestock	Other Livestock	14
5	ForestFrsHnt	Forestry, Fishing, & Hunting	15-19
6	OilGas	Oil & Gas	20-21,37-38
7	Coal	Coal	22
8	OtherMining	Other Mining	23-36, 39, 40
9	BiomassGen	Biomass electricity generation	47
10	CoalsGen	Coal-fired electricity generation	42 and 48
11	GasGen	Gas-fired electricity generation	42 and 48
12	HydroGen	Hydroelectric generation	41
13	NuclearGen	Nuclear electricity generation	43
14	RenewGen	Renewable electricity generation	44 and 45
15	ElecDist	Electricity distribution	49
16	NatGasDist	Natural gas distribution	50
17	WaterSewage	Water and sewage services	51
18	ResidConstrt	Residential Construction	59-61
19	OthConstruct	Highway Construction	56
20	HwyBrdgCons	Other Non-Residential Construction	52-55, 57-58
21	OthMaintain	Highway Maintenance	64
22	MRstreets	Other Maintenance	62-63?
23	FoodProc	Food Processing	65-105
24	BevTobManu	Beverage & Tobacco Product Manufacturing	106-111
25	Textiles	Textile & Textile Product Manufacturing	112-123
26	Apparels	Apparel	124-130
27	LeathFtwr	Leather & Allied Products	131-133
28	WoodProds	Wood Product Manufacturing	134-145
29	PulpPaperPbd	Paper Mills	146-153
30	Printing	Printing & Related Support Activities	154, 155
31	PetrolRefine	Petroleum Refineries	156
32	OthPetrolCl	Other Petroleum & Coal Products	157-160
33	Chemicals	Chemicals	161-187

TERM Sector	Short names	Description	Bridging to IMPLAN Sectors
34	RubPlastic	Rubber & Plastics	188-198
35	NonMetMinPrd	Non-Metallics	199-216
36	PrimMetals	Primary Metal Manufacturing	217-230
37	FabriMetals	Fabricated Metal Product Manufacturing	231-261
38	AgriMachinry	Agriculture Machinery	262-266
39	IndustrMach	Industrial Machinery	267-271
40	CommrcMach	Commercial Machinery	272-274
41	AirConHeat	Ventilation, Heating & Air-Conditioning	275-277
42	MetalWkMach	Metalworking Machinery	278-282
43	TurbnEngine	Engines & Turbines	283-286
44	OtherMach	Other General Purpose Machinery Manufacturing	287-300
45	Computers	Computers	301
46	CmptrStorage	Computer Storage Devices	302
47	ComptrTrmEtc	Computer Terminals & Other Peripheral Equipment	303
48	CommunicEqp	Communications Equipment	304-306
49	MscElctEqp	Miscellaneous Electronic Equipment	307, 308, 310-319
50	Semicondctr	Semiconductors & Related Devices	309
51	ElecInstrmnt	Electronic Instruments	320-324
52	HholdEqp	Household Equipment, Appliances, and Component Manufacturing	325-342
53	MVPManu	Motor Vehicle and Parts Manufacturing	343-356
54	AerospaceMan	Aerospace Product & Parts Manufacturing	357-361
55	RlrdCars	Railroad Rolling Stock Manufacturing	362
56	ShipsBoats	Ship & Boat Building	363-364
57	OthTrnEqp	Other Transportation Equipment Manufacturing	365-367
58	Furniture	Furniture & Related Product Manufacturing	368-378
59	MiscManuf	Miscellaneous Manufacturing	379-394
60	WholesaleTr	Wholesale Trade	395
61	AirTrans	Air Transport	408
62	RailTrans	Rail Transport	409
63	WaterTrans	Water Transport	410
64	TruckTrans	Truck Transport	411
65	GrdPassTrans	Transit and Ground Passenger Transport	412
66	Pipeline	Pipelines	413
67	OthTransprt	Other Transportation	414-415
68	Warehousing	Warehousing	416

TERM Sector	Short names	Description	Bridging to IMPLAN Sectors
69	RetailTr	Retail Trade	396-407
70	Publishing	Publishing Industries	417-422
71	MovieSound	Motion Picture & Sound Recording Industry	423, 424
72	BroadcastSrv	Broadcasting	425, 426, 432
73	Telecomm	Telecommunications	427-429
74	InfoSvce	Information Services	431
75	DataProcScv	Data Processing Services	430
76	FinancBank	Finance & Banking	433-439
77	RealEstate	Real Estate	440
78	RentLease	Rental & Leasing Services	442-445
79	AssetLessors	Lessors of Nonfinancial Intangible Assets	446
80	PrfSciTchSrv	Professional, Scientific, Technical, Administrative, & Support Services	447-470
81	WasteMgmt	Waste Management Services	471
82	Education	Education Services	472-474
83	HealthSocAs	Health Care & Social Assistance	475-487
84	ArtsRecreat	Arts, Entertainment & Recreation	488-498
85	Accommodatn	Accommodations	499-500
86	EatDrinkPlce	Eating & Drinking Places	501-503
87	OthService	Other Services	504-517
88	GovEnterprs	Owner-Occupied Dwellings	441
89	StaLocGov	Government Enterprises	519-525, 526-530
90	OwnOccDwell	State & Local Government	531- 534
91	FedGovt	Federal Government	518, 535, 536
92	Holiday	Holiday	--
93	FgnHol	Foreign Holidays	--
94	ExpTour	Tourism Exports (including Purchases by Foreigners in Embassies etc.)	--
95	ExpEdu	Education Exports	--
96	WT_EXP	Water Transport Exports	--
97	AT_EXP	Air Transport Exports	--

Appendix C. Income Distribution Matrices

Appendix Table C1. Employee Compensation Distribution Matrix for California, 2018

(millions of 2018$)

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
01. Crops	0	0	3,082	3,781	974	426	168	135	151	8,717
02. Poultry & Eggs	0	0	35	43	11	5	2	2	2	98
03. Livestock	0	0	145	177	46	20	8	6	7	409
04. Other Livestock	0	0	10	12	3	1	1	0	0	27
05. Forestry, Fishing, & Hunting	0	0	0	3	46	64	15	3	0	130
06. Oil & Gas	0	0	1	4	28	83	110	97	130	453
07. Coal	0	0	0	0	2	4	2	2	1	10
08. Other Mining	0	0	4	48	177	415	220	163	70	1,097
09. Biomass electricity generation	0	0	0	0	1	3	6	12	4	26
10-11. Coal-fired and Gas-fired electricity generation	0	0	0	4	24	109	199	410	144	891
12. Hydroelectric generation	0	0	0	1	3	15	28	57	20	124
13. Nuclear electricity generation	0	0	0	2	10	45	82	168	59	364
14. Renewable electricity generation	0	0	0	1	5	23	42	86	30	188
15. Electricity distribution	0	0	0	1	7	30	55	112	39	244
16. Natural gas distribution	0	0	1	15	88	403	735	1,512	531	3,285
17. Water and sewage services	0	0	0	1	9	39	71	146	51	317
18. Residential Construction	0	2	123	756	2,091	4,711	3,323	2,881	967	14,854
19. Highway Construction	0	0	37	225	624	1,405	991	859	289	4,431
20. Other Non-Residential Construction	0	4	297	1,824	5,047	11,370	8,021	6,954	2,335	35,853
21. Highway Maintenance	0	0	28	170	469	1,057	746	647	217	3,334
22. Other Maintenance	0	1	117	721	1,994	4,493	3,169	2,748	922	14,166
23. Food Processing	0	1	780	2,107	2,302	2,128	875	816	716	9,725
24. Beverage & Tobacco Product Manufacturing	0	0	170	589	912	1,065	586	436	375	4,133
25. Textile & Textile Product Manufacturing	0	0	89	175	167	126	56	63	59	734
26. Apparel	0	1	362	540	257	256	192	242	210	2,060
27. Leather & Allied Products	0	0	12	45	24	9	3	4	9	106
28. Wood Product Manufacturing	0	0	98	336	383	295	110	97	72	1,391
29. Paper Mills	0	0	59	221	372	369	120	144	113	1,399
30. Printing & Related Support Activities	0	0	148	418	607	671	207	224	172	2,447
31. Petroleum Refineries	0	0	3	14	42	173	378	395	235	1,241
32. Other Petroleum & Coal Products	0	0	0	1	4	18	39	41	24	128
33. Chemicals	0	0	95	401	789	1,572	1,266	2,181	3,126	9,431
34. Rubber & Plastics	0	0	151	519	624	565	241	299	272	2,672
35. Non-Metallics	0	0	99	582	1,164	1,370	539	462	212	4,427
36. Primary Metal Manufacturing	0	0	33	175	273	255	120	104	88	1,048

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
37. Fabricated Metal Product	0	0	248	1,293	2,207	2,907	992	960	940	9,547
38. Agriculture Machinery	0	0	5	29	53	88	56	78	89	398
39. Industrial Machinery	0	0	34	181	332	552	348	487	561	2,496
40. Commercial Machinery	0	0	16	84	154	255	161	225	259	1,153
41. Ventilation, Heating & Air-Conditioning	0	0	5	26	48	79	50	70	80	357
42. Metalworking Machinery	0	0	10	54	99	164	103	144	167	741
43. Engines & Turbines	0	0	9	47	87	144	91	127	146	651
44. Other General Purpose Machinery Manufacturing	0	0	17	92	169	282	178	248	286	1,273
45. Computers	0	2	196	866	1,801	3,639	3,982	9,269	14,511	34,265
46. Computer Storage Devices	0	0	8	36	75	151	165	383	600	1,418
47. Computer Terminals & Other Peripheral Equipment	0	0	12	55	114	231	252	588	920	2,172
48. Communications Equipment	0	0	6	24	36	40	31	52	68	257
49. Miscellaneous Electronic Equipment	0	0	27	103	158	175	134	225	295	1,116
50. Semiconductors & Related Devices	0	0	25	96	148	164	125	211	277	1,046
51. Electronic Instruments	0	0	7	26	40	44	33	56	74	279
52. Household Equipment, Appliances, and Component Manufacturing	0	0	7	26	40	45	34	57	75	284
53. Motor Vehicle and Parts Manufacturing	0	0	20	136	227	427	379	588	698	2,474
54. Aerospace Product & Parts Manufacturing	0	0	78	542	905	1,708	1,512	2,350	2,789	9,885
55. Railroad Rolling Stock Manufacturing	0	0	1	5	9	16	14	23	27	95
56. Ship & Boat Building	0	0	6	41	69	130	115	179	212	753
57. Other Transportation Equipment Manufacturing	0	0	2	13	22	42	37	58	69	244
58. Furniture & Related Product Manufacturing	0	0	140	458	563	505	207	172	182	2,227
59. Miscellaneous Manufacturing	0	0	144	666	1,065	1,544	945	1,504	1,849	7,717
60. Wholesale Trade	6	43	1,217	5,297	8,602	11,238	7,764	8,423	10,012	52,602
61. Air Transport	0	0	28	223	584	1,745	305	415	2,628	5,926
62. Rail Transport	0	0	0	1	38	289	185	135	29	677
63. Water Transport	0	1	22	22	63	134	110	90	109	553
64. Truck Transport	0	0	236	2,401	4,523	8,134	700	703	385	17,082
65. Transit and Ground Passenger Transport	0	0	117	678	1,066	665	83	52	41	2,702
66. Pipelines	0	0	0	1	12	31	37	41	3	125
67. Other Transportation	0	1	260	1,240	1,934	3,312	1,709	879	737	10,070
68. Warehousing	0	1	427	1,783	2,789	2,763	729	365	176	9,034
69. Retail Trade	1	33	13,498	23,012	19,473	11,573	4,892	4,349	4,347	81,177
70. Publishing Industries	0	1	51	213	536	1,560	1,922	4,240	6,120	14,643
71. Motion Picture & Sound Recording Industry	2	8	381	692	1,055	1,928	2,160	3,140	3,784	13,151
72. Broadcasting	1	2	42	156	481	756	869	1,070	1,041	4,418
73. Telecommunications	2	10	66	281	903	3,408	3,922	3,904	2,421	14,916

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
74. Information Services	0	0	18	84	363	1,091	1,863	4,424	7,246	15,090
75. Data Processing Services	0	0	8	52	149	553	889	2,149	3,488	7,287
76. Finance & Banking	21	25	456	2,787	6,478	12,189	9,947	14,100	24,491	70,495
77. Real Estate	5	51	1,151	3,544	5,632	6,016	4,565	5,341	4,373	30,678
78. Rental & Leasing Services	0	1	215	516	884	968	423	396	319	3,722
79. Lessors of Nonfinancial Intangible Assets	0	0	1	6	14	26	33	49	105	233
80. Professional, Scientific, Technical, Administrative, & Support Services	5	25	4,894	16,066	23,297	36,347	30,378	56,497	72,635	240,144
81. Waste Management Services	0	0	93	328	739	992	728	237	194	3,311
82. Education Services	6	40	1,262	8,066	17,236	27,629	26,445	31,521	13,404	125,609
83. Health Care & Social Assistance	-1	4	10,561	18,612	28,318	31,933	20,964	40,420	36,312	187,124
84. Arts, Entertainment & Recreation	1	6	1,964	3,112	2,619	2,815	1,642	1,289	1,357	14,805
85. Accommodations	0	6	1,382	3,203	2,815	1,799	662	569	322	10,758
86. Eating & Drinking Places	0	0	14,074	19,823	7,670	3,552	1,082	359	337	46,898
87. Other Services	1	9	2,384	5,274	5,418	6,311	3,334	2,801	1,874	27,405
88. Owner-Occupied Dwellings	0	0	0	0	0	0	0	0	0	0
89. Government Enterprises	0	0	44	239	859	2,353	2,486	3,446	1,016	10,442
90. State & Local Government	0	2	373	2,051	7,371	20,195	21,335	29,574	8,719	89,621
91. Federal Government	0	1	83	493	2,398	8,535	4,963	6,592	1,939	25,003
Total	**50**	**283**	**62,313**	**139,065**	**182,316**	**257,764**	**189,797**	**268,131**	**246,790**	**1,346,510**

Appendix Table C2. Proprietors' Income Distribution Matrix for California, 2018

(millions of 2018$)

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
01. Crops	0	111	152	213	503	837	1,479	1,225	4,925	9,446
02. Poultry & Eggs	0	2	3	4	10	17	30	25	100	192
03. Livestock	0	23	31	44	103	172	304	252	1,011	1,939
04. Other Livestock	0	2	2	3	8	13	22	18	74	141
05. Forestry, Fishing, & Hunting	0	13	18	26	61	101	179	148	595	1,140
06. Oil & Gas	0	19	26	37	87	144	255	211	848	1,627
07. Coal	0	0	0	0	0	0	0	0	1	1
08. Other Mining	0	0	0	0	0	1	1	1	4	8
09. Biomass electricity generation	0	3	4	6	13	22	38	32	128	245
10-11. Coal-fired and Gas-fired electricity generation	0	2	2	3	7	12	22	18	73	140
12. Hydroelectric generation	0	1	1	2	4	6	11	9	36	69
13. Nuclear electricity generation	0	0	0	0	0	0	0	0	0	0
14. Renewable electricity generation	0	1	2	2	6	10	17	14	57	110
15. Electricity distribution	0	0	0	0	1	1	2	2	8	16
16. Natural gas distribution	0	1	1	2	4	6	11	9	37	71
17. Water and sewage services	0	4	6	9	20	34	59	49	198	379
18. Residential Construction	0	137	189	263	623	1,037	1,831	1,517	6,096	11,693
19. Highway Construction	0	12	16	23	53	89	157	130	523	1,002
20. Other Non-Residential Construction	0	102	140	195	461	767	1,355	1,122	4,511	8,652
21. Highway Maintenance	0	12	17	24	57	94	166	138	554	1,062
22. Other Maintenance	0	50	69	96	228	379	670	555	2,231	4,279
23. Food Processing	0	9	13	18	42	70	124	103	412	790
24. Beverage & Tobacco Product Manufacturing	0	14	19	26	63	104	184	153	613	1,176
25. Textile & Textile Product Manufacturing	0	0	0	1	2	3	4	4	15	28
26. Apparel	0	4	6	8	19	31	54	45	181	348
27. Leather & Allied Products	0	0	0	0	0	1	1	1	4	7
28. Wood Product Manufacturing	0	0	0	0	-1	-1	-2	-2	-8	-16
29. Paper Mills	0	3	4	5	12	19	34	28	114	218
30. Printing & Related Support Activities	0	4	6	8	19	32	56	46	186	357
31. Petroleum Refineries	0	0	0	0	0	1	1	1	4	7
32. Other Petroleum & Coal Products	0	0	0	0	1	1	2	2	8	14
33. Chemicals	0	6	8	11	25	42	75	62	249	478
34. Rubber & Plastics	0	3	4	6	15	24	43	36	144	275
35. Non-Metallics	0	1	1	2	4	6	11	9	36	69
36. Primary Metal Manufacturing	0	-3	-4	-5	-13	-21	-37	-31	-124	-238
37. Fabricated Metal Product	0	6	8	12	28	46	81	67	269	517
38. Agriculture Machinery	0	0	0	1	1	2	4	3	14	26

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
39. Industrial Machinery	0	1	1	1	3	4	8	6	25	48
40. Commercial Machinery	0	1	1	1	2	4	7	6	23	43
41. Ventilation, Heating & Air-Conditioning	0	0	0	0	1	2	3	3	11	22
42. Metalworking Machinery	0	1	1	2	4	6	11	9	37	71
43. Engines & Turbines	0	0	0	0	1	1	2	1	6	11
44. Other General Purpose Machinery Manufacturing	0	1	1	2	4	6	11	9	37	71
45. Computers	0	0	0	0	0	0	0	0	0	0
46. Computer Storage Devices	0	0	0	0	0	0	0	0	0	0
47. Computer Terminals & Other Peripheral Equipment	0	0	0	0	0	0	0	0	0	1
48. Communications Equipment	0	0	0	0	0	0	0	0	0	1
49. Miscellaneous Electronic Equipment	0	0	0	0	0	0	1	1	2	4
50. Semiconductors & Related Devices	0	0	0	0	0	0	0	0	0	0
51. Electronic Instruments	0	0	0	0	0	0	0	0	0	1
52. Household Equipment, Appliances, and Component Manufacturing	0	0	0	0	1	1	2	2	8	15
53. Motor Vehicle and Parts Manufacturing	0	3	4	6	13	22	38	32	127	244
54. Aerospace Product & Parts Manufacturing	0	0	0	0	1	1	2	2	6	12
55. Railroad Rolling Stock Manufacturing	0	0	0	0	0	0	0	0	0	0
56. Ship & Boat Building	0	0	0	0	0	0	0	0	1	2
57. Other Transportation Equipment Manufacturing	0	0	0	0	0	0	0	0	1	2
58. Furniture & Related Product Manufacturing	0	4	5	7	18	29	52	43	173	331
59. Miscellaneous Manufacturing	0	2	2	3	8	12	22	18	74	141
60. Wholesale Trade	0	50	68	95	225	374	661	548	2,200	4,221
61. Air Transport	0	4	5	7	18	29	52	43	173	332
62. Rail Transport	0	0	0	0	0	-1	-1	-1	-4	-7
63. Water Transport	0	0	0	0	0	0	0	0	-1	-2
64. Truck Transport	0	92	127	177	418	695	1,228	1,018	4,089	7,844
65. Transit and Ground Passenger Transport	0	18	24	34	80	133	235	195	784	1,503
66. Pipelines	0	1	2	2	5	9	15	13	51	98
67. Other Transportation	0	29	40	56	131	219	386	320	1,286	2,467
68. Warehousing	0	4	5	7	16	27	47	39	156	299
69. Retail Trade	0	212	291	407	961	1,599	2,824	2,340	9,405	18,040
70. Publishing Industries	0	4	5	7	17	28	50	41	166	318
71. Motion Picture & Sound Recording Industry	0	4	5	8	18	30	52	43	174	333
72. Broadcasting	0	210	288	402	950	1,581	2,793	2,314	9,301	17,839
73. Telecommunications	0	0	0	1	1	2	4	3	12	23
74. Information Services	0	0	0	0	1	1	2	2	8	16
75. Data Processing Services	0	2	3	5	11	18	32	26	105	202

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
76. Finance & Banking	0	68	93	130	306	509	900	746	2,996	5,747
77. Real Estate	0	374	513	717	1,695	2,820	4,980	4,127	16,584	31,808
78. Rental & Leasing Services	0	44	61	85	200	333	588	487	1,957	3,753
79. Lessors of Nonfinancial Intangible Assets	0	6	8	11	26	43	76	63	254	487
80. Professional, Scientific, Technical, Administrative, & Support Services	0	535	735	1,026	2,426	4,037	7,130	5,908	23,743	45,540
81. Waste Management Services	0	0	1	1	2	4	6	5	21	40
82. Education Services	0	15	20	29	68	112	198	164	661	1,268
83. Health Care & Social Assistance	0	203	279	390	922	1,534	2,710	2,246	9,024	17,309
84. Arts, Entertainment & Recreation	0	101	139	194	458	763	1,347	1,116	4,486	8,605
85. Accommodations	0	7	10	14	33	55	96	80	321	615
86. Eating & Drinking Places	0	82	112	157	371	618	1,091	904	3,634	6,969
87. Other Services	0	314	431	602	1,423	2,368	4,183	3,466	13,928	26,715
88. Owner-Occupied Dwellings	0	0	0	0	0	0	0	0	0	0
89. Government Enterprises	0	0	0	0	0	0	0	0	0	0
90. State & Local Government	0	0	0	0	0	0	0	0	0	0
91. Federal Government	0	0	0	0	0	0	0	0	0	0
Total	**0**	**2,934**	**4,028**	**5,626**	**13,301**	**22,134**	**39,089**	**32,391**	**130,170**	**249,672**

Appendix Table C3. Dividend and Other Property Income Distribution Matrix for California, 2018

(millions of 2018$)

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
01. Crops	17	47	49	63	171	233	344	246	1,118	2,289
02. Poultry & Eggs	0	1	1	1	2	2	4	3	12	24
03. Livestock	4	12	12	16	42	58	85	61	278	568
04. Other Livestock	1	2	2	2	6	8	12	9	40	83
05. Forestry, Fishing, & Hunting	2	7	7	9	25	34	50	35	161	330
06. Oil & Gas	9	26	27	34	92	126	186	133	604	1,235
07. Coal	0	0	0	0	0	1	1	1	3	6
08. Other Mining	4	10	10	13	36	49	73	52	236	484
09. Biomass electricity generation	1	3	3	4	12	16	23	17	76	155
10-11. Coal-fired and Gas-fired electricity generation	18	49	51	64	176	239	353	252	1,147	2,348
12. Hydroelectric generation	1	4	4	5	14	20	29	21	94	193
13. Nuclear electricity generation	5	14	15	19	52	71	105	75	341	697
14. Renewable electricity generation	10	26	27	35	94	128	189	135	616	1,260
15. Electricity distribution	5	15	16	20	54	73	108	77	352	720
16. Natural gas distribution	8	22	23	29	78	107	157	113	512	1,048
17. Water and sewage services	3	9	10	12	33	45	67	48	218	445
18. Residential Construction	63	174	181	230	629	856	1,263	903	4,109	8,410
19. Highway Construction	6	18	18	23	63	86	127	91	414	848
20. Other Non-Residential Construction	53	147	153	194	529	721	1,063	760	3,459	7,079
21. Highway Maintenance	6	16	16	21	57	77	114	81	370	756
22. Other Maintenance	24	65	67	86	234	318	469	335	1,526	3,124
23. Food Processing	33	89	93	118	323	440	649	464	2,111	4,320
24. Beverage & Tobacco Product Manufacturing	13	35	36	46	126	171	253	181	822	1,683
25. Textile & Textile Product Manufacturing	1	3	3	4	12	16	24	17	77	157
26. Apparel	2	5	5	7	18	25	36	26	118	242
27. Leather & Allied Products	0	0	0	0	0	0	0	0	-2	-3
28. Wood Product Manufacturing	3	8	8	10	28	38	56	40	183	374
29. Paper Mills	5	13	13	17	45	62	91	65	296	605
30. Printing & Related Support Activities	4	10	10	13	36	49	72	51	234	480
31. Petroleum Refineries	61	169	175	223	609	829	1,223	874	3,977	8,141
32. Other Petroleum & Coal Products	3	8	8	10	28	38	57	41	185	378
33. Chemicals	175	481	501	637	1,738	2,365	3,489	2,495	11,352	23,233
34. Rubber & Plastics	7	18	19	24	65	88	130	93	424	867
35. Non-Metallics	6	16	16	21	56	76	113	81	367	750
36. Primary Metal Manufacturing	2	5	5	7	19	26	38	27	123	253
37. Fabricated Metal Product	19	51	53	68	185	252	371	265	1,207	2,471
38. Agriculture Machinery	2	6	6	7	20	27	40	29	131	268

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
39. Industrial Machinery	1	2	2	3	9	12	17	12	56	115
40. Commercial Machinery	4	12	12	15	42	57	84	60	272	558
41. Ventilation, Heating & Air-Conditioning	1	4	4	5	14	19	28	20	90	184
42. Metalworking Machinery	1	4	4	5	14	19	28	20	90	183
43. Engines & Turbines	2	5	6	7	19	26	39	28	126	258
44. Other General Purpose Machinery Manufacturing	4	11	11	14	39	53	79	56	257	525
45. Computers	97	265	276	351	957	1,303	1,922	1,374	6,253	12,798
46. Computer Storage Devices	7	20	21	27	72	98	145	104	473	967
47. Computer Terminals & Other Peripheral Equipment	4	11	11	14	38	52	77	55	251	513
48. Communications Equipment	6	17	18	22	61	84	123	88	401	821
49. Miscellaneous Electronic Equipment	27	73	76	97	265	361	532	380	1,730	3,541
50. Semiconductors & Related Devices	32	87	91	116	316	430	634	453	2,062	4,219
51. Electronic Instruments	8	21	22	28	75	102	151	108	491	1,004
52. Household Equipment, Appliances, and Component Manufacturing	4	12	12	16	43	59	87	62	283	579
53. Motor Vehicle and Parts Manufacturing	12	34	35	45	122	167	246	176	799	1,636
54. Aerospace Product & Parts Manufacturing	18	50	52	66	181	247	364	260	1,183	2,422
55. Railroad Rolling Stock Manufacturing	0	0	0	0	1	1	2	1	6	11
56. Ship & Boat Building	0	1	1	1	2	3	5	3	15	31
57. Other Transportation Equipment Manufacturing	1	2	2	2	6	8	12	9	40	81
58. Furniture & Related Product Manufacturing	2	5	5	6	18	24	35	25	115	235
59. Miscellaneous Manufacturing	21	57	60	76	207	282	416	297	1,353	2,769
60. Wholesale Trade	162	445	463	589	1,606	2,186	3,225	2,306	10,492	21,475
61. Air Transport	23	63	66	83	227	309	457	326	1,485	3,040
62. Rail Transport	2	6	7	8	23	31	46	33	150	306
63. Water Transport	5	14	15	19	52	71	105	75	340	696
64. Truck Transport	8	23	23	30	81	111	163	117	532	1,088
65. Transit and Ground Passenger Transport	7	18	19	24	66	90	133	95	434	888
66. Pipelines	0	0	0	1	1	2	3	2	9	19
67. Other Transportation	21	59	61	77	211	288	424	303	1,381	2,826
68. Warehousing	8	21	22	28	75	102	151	108	491	1,005
69. Retail Trade	108	297	310	394	1,074	1,462	2,157	1,543	7,018	14,364
70. Publishing Industries	89	244	254	323	881	1,199	1,769	1,265	5,756	11,780
71. Motion Picture & Sound Recording Industry	190	522	543	690	1,884	2,564	3,783	2,705	12,307	25,188
72. Broadcasting	58	158	164	209	570	776	1,144	818	3,722	7,618
73. Telecommunications	144	396	412	524	1,429	1,945	2,870	2,052	9,336	19,108
74. Information Services	4	10	10	13	36	48	71	51	233	476
75. Data Processing Services	1	3	3	4	10	14	20	14	65	134

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
76. Finance & Banking	211	579	603	767	2,093	2,849	4,203	3,005	13,673	27,984
77. Real Estate	801	2,197	2,287	2,908	7,937	10,803	15,937	11,396	51,846	106,113
78. Rental & Leasing Services	30	82	86	109	297	404	596	426	1,939	3,968
79. Lessors of Nonfinancial Intangible Assets	67	183	190	242	660	898	1,325	947	4,310	8,821
80. Professional, Scientific, Technical, Administrative, & Support Services	281	771	802	1,020	2,783	3,788	5,589	3,996	18,181	37,212
81. Waste Management Services	8	22	23	30	81	110	162	116	527	1,078
82. Education Services	7	20	20	26	71	96	142	101	461	944
83. Health Care & Social Assistance	86	237	247	314	857	1,166	1,720	1,230	5,596	11,453
84. Arts, Entertainment & Recreation	50	138	144	183	498	678	1,001	716	3,256	6,664
85. Accommodations	21	56	59	75	204	277	409	292	1,330	2,723
86. Eating & Drinking Places	71	194	202	256	700	952	1,405	1,004	4,570	9,353
87. Other Services	-2	-6	-6	-7	-20	-28	-41	-29	-134	-273
88. Owner-Occupied Dwellings	461	1,265	1,317	1,674	4,570	6,220	9,175	6,561	29,850	61,094
89. Government Enterprises	35	95	99	126	343	467	690	493	2,243	4,591
90. State & Local Government	91	248	258	329	897	1,220	1,800	1,287	5,857	11,988
91. Federal Government	187	514	535	681	1,857	2,528	3,729	2,667	12,132	24,830
Total	**4,064**	**11,147**	**11,604**	**14,754**	**40,266**	**54,803**	**80,849**	**57,814**	**263,023**	**538,325**

Appendix Table C4. Personal Transfer Receipts Distribution Matrix for California, 2018

(millions of 2018$)

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
01. Crops	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
02. Poultry & Eggs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
03. Livestock	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
04. Other Livestock	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
05. Forestry, Fishing, & Hunting	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
06. Oil & Gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
07. Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
08. Other Mining	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
09. Biomass electricity generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
10-11. Coal-fired and Gas-fired electricity generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
12. Hydroelectric generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
13. Nuclear electricity generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
14. Renewable electricity generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
15. Electricity distribution	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
16. Natural gas distribution	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
17. Water and sewage services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
18. Residential Construction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
19. Highway Construction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
20. Other Non-Residential Construction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
21. Highway Maintenance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
22. Other Maintenance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
23. Food Processing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
24. Beverage & Tobacco Product Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
25. Textile & Textile Product Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
26. Apparel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
27. Leather & Allied Products	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
28. Wood Product Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
29. Paper Mills	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
30. Printing & Related Support Activities	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
31. Petroleum Refineries	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
32. Other Petroleum & Coal Products	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
33. Chemicals	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
34. Rubber & Plastics	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
35. Non-Metallics	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
36. Primary Metal Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
37. Fabricated Metal Product	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
38. Agriculture Machinery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0

Sector	<10k	10-15k	15-25k	25-35k	35-50k	50-75k	75-100k	100-150k	150k+	Total
39. Industrial Machinery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
40. Commercial Machinery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
41. Ventilation, Heating & Air-Conditioning	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
42. Metalworking Machinery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
43. Engines & Turbines	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
44. Other General Purpose Machinery Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
45. Computers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
46. Computer Storage Devices	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
47. Computer Terminals & Other Peripheral Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
48. Communications Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
49. Miscellaneous Electronic Equipment	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
50. Semiconductors & Related Devices	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
51. Electronic Instruments	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
52. Household Equipment, Appliances, and Component Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
53. Motor Vehicle and Parts Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
54. Aerospace Product & Parts Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
55. Railroad Rolling Stock Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
56. Ship & Boat Building	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
57. Other Transportation Equipment Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
58. Furniture & Related Product Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
59. Miscellaneous Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
60. Wholesale Trade	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
61. Air Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
62. Rail Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
63. Water Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
64. Truck Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
65. Transit and Ground Passenger Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
66. Pipelines	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
67. Other Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
68. Warehousing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
69. Retail Trade	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
70. Publishing Industries	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
71. Motion Picture & Sound Recording Industry	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
72. Broadcasting	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
73. Telecommunications	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
74. Information Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
75. Data Processing Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0

Sector	**<10k**	**10-15k**	**15-25k**	**25-35k**	**35-50k**	**50-75k**	**75-100k**	**100-150k**	**150k+**	**Total**
76. Finance & Banking	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
77. Real Estate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
78. Rental & Leasing Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
79. Lessors of Nonfinancial Intangible Assets	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
80. Professional, Scientific, Technical, Administrative, & Support Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
81. Waste Management Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
82. Education Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
83. Health Care & Social Assistance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
84. Arts, Entertainment & Recreation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
85. Accommodations	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
86. Eating & Drinking Places	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
87. Other Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
88. Owner-Occupied Dwellings	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
89. Government Enterprises	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
90. State & Local Government	9,138.6	24,626.9	14,848.7	11,454.5	15,292.2	12,922.5	11,729.6	5,392.2	14,905.5	120,311
91. Federal Government	15,089.8	40,890.8	24,941.8	19,510.9	26,771.5	23,473.9	22,733.7	11,358.3	36,138.6	220,909
Total	**24,228.5**	**65,517.7**	**39,790.5**	**30,965.4**	**42,063.7**	**36,396.4**	**34,463.3**	**16,750.5**	**51,044.1**	**341,220**