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A data-driven framework to evaluate the indirect economic impacts of transportation infrastructure disruptions

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A R T I C L E I N F O

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A B S T R A C T

Transportation systems are critical to the sustainable development and economic vitality of cities. However, they are vulnerable to disruptions that can result from natural and man-made disasters as well as maintenance activities that may require temporary closure of road segments. Previous research indicated that transportation disruptions can cause not only significant direct economic losses, but also substantial indirect impacts, which are difficult to analyze and quantify. The comprehensive estimation of the indirect economic impacts calls for interdisciplinary research frameworks. This study introduces a new analytical framework for estimating the indirect economic impacts that are caused by various direct effects of transportation disruptions, including building and content losses, business interruptions, freight flow perturbations, and passenger flow perturbations. One of the state-of-the-art Computable General Equilibrium (CGE) models, the TERM model, is leveraged to calculate the indirect economic impacts, fed with information on transportation disruptions generated by explicit transportation network models through a series of well-built model linkages. These linkages are set based on a thorough investigation of the potential indirect impacts due to transportation disruptions. Besides, critical data that are required to achieve a comprehensive and accurate estimation of the indirect economic impacts are identified. Potential double counting issues related to the implementation of the framework and mitigation solutions are discussed. To deploy the framework, a case study of a hypothetical earthquake scenario in the Greater Los Angeles Area was conducted. The indirect economic impacts of transportation disruptions caused by earthquake-induced bridge damages were estimated and analyzed. Simulation results indicated that millions of dollars could be lost in this case due to road transportation network disruptions, and the geographical distribution of those losses could be quantified. This study lays a foundation for further interdisciplinary research on the integration of transportation system analyses with economic models.

1. Introduction

As one of the key lifeline systems, transportation systems play a vital role in the functioning of urban cities. However, transportation systems are vulnerable to various natural and man-made disasters, such as earthquakes, hurricanes, terrorist attacks, strikes, etc. Worse still, due to their networked nature, damage to a single component can trigger non-linear failure dynamics, i.e., cascading

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failures which often lead to intolerable losses in the functionality of transportation networks [1,2]. Given the critical role transportation systems play in the mobility of commodities and people, transportation infrastructure disruptions can cause extensive impacts on the economic system through a set of mechanisms. For example, port disruptions can lead to extra storage costs and production losses for downstream industries due to a lack of raw materials. In such a scenario, retailers and final users such as households will also be affected. The current COVID-19 pandemic highlighted how essential mobility is to the local, regional, national, and global economies.

Researchers from various domains have investigated the indirect economic losses caused by transportation perturbations resulting from a wide spectrum of man-made or natural hazards [3–5] and other singular disruption events [6,7]. Some researchers focused on the upstream and downstream impacts cascading through supply chains [8,9]. Regional and national-wide economic impacts have been investigated as well. Approaches from both engineering and economic perspectives have been applied by different researchers. However, investigations from both types of approaches demonstrate characteristic shortcomings. Studies implementing engineering approaches tend to resort to only simple estimations of the economic impacts based on linear calculations,[1] neglecting the indirect economic impacts of transportation perturbations across regions and industries through transportation flows and economic activities. Research on transport-related economic losses caused by the Niigata-Chuetsu earthquake shows that over 40% of the total losses happened in regions that were not directly affected by the earthquake [4]. On the other hand, researchers using economic approaches to estimate the impacts of transportation disruptions have also not achieved a convincingly comprehensive estimation of the total (direct and indirect) economic impacts of transportation disruptions yet. For example, direct impacts such as physical damages to the infrastructure and other building stock (where the hazard does damage beyond the transportation infrastructure) are not fully incorporated into the estimation process [10]. It is seen that most studies in this area of research focus on the indirect economic impacts originating from commodity flow perturbations. Only a few studies include an accounting of the indirect impacts arising from perturbations in passenger flows [4,11–13]. This shows that the problem has typically been studied in an abstract manner disregarding passenger flows in the quantification of disruption, despite data showing the significance of such disruptions [14,15]. For example, data from the Loma Prieta Earthquake in 1989 reveals that the hazard caused approximately a quarter-million daily users of the Oakland/San Francisco Bay Bridge to change their travel patterns when the bridge was closed for 30 days [16]. Thousands of commuters suffered from increased costs or had to change their commuting modes. In addition, it is essential to note that transportation network models and traditional economic models are not readily interoperable due to a mismatch between inputs, outputs, and modeling assumptions. And transportation perturbations can have influences on the economy in various ways [17]. In this context, a comprehensive estimation of the economic impacts of transportation disruptions is of significance to disaster risk management as well as disaster response and recovery. For example, a comprehensive estimation of economic impacts is fundamental for assessing the effectiveness of disaster mitigation measures (such as hardening critical bridges before hurricanes) and resilience tactics (such as prioritizing repair and reconstruction projects) [18,19].

The objective of this paper is to introduce a new interdisciplinary assessment framework for investigating transportation system disruptions and calculating the indirect economic impacts caused by a series of direct effects of transportation disruptions. An economic impact analysis methodology, Computable General Equilibrium (CGE) modeling, is leveraged, considering its well-established advantages such as overcoming linearity/rigidity of traditional models, allowing for price perturbation, substitution, and behavioral response, etc. [20–22]. Information on transportation system disruption is incorporated by investigating methodological improvements considering multiple linkages between transportation disruptions and economic activities. Both commodity flow perturbation and passenger flow perturbation are taken into consideration in the proposed framework. Indirect economic impacts caused by potential capital losses and business income losses can be investigated as well. Besides, potential double counting issues and solutions are discussed. Meanwhile, a wide range of critical data needs to achieve a comprehensive and accurate estimation of the indirect economic impacts due to transportation infrastructure disruptions are identified. The paper then introduces a case study in the Greater Los Angeles Area where the proposed framework was tested. In this case study, the total economic impacts of road transportation network disruptions caused by the closure of several critical corridors due to a scenario earthquake were calculated. This framework contributes to the further integration of transportation system analyses and economic models.

This paper is organized as follows. Section 2 presents a bibliographical review that sheds light on previous research in this domain. Based on the literature review, the research gaps in this area are identified. Section 3 illustrates the integrated framework designed to address the identified gaps. Section 4 presents the implementation of the framework and the results for the Greater Los Angeles Area case study. Discussion of the results and the limitations of the current work are presented in Section 5. Finally, section 6 concludes the paper with ideas for future work.

2. Literature review

2.1. Types of disruptions in transportation systems

Critically analyzing the literature in this area shows that many researchers focused specifically on port disruptions and induced commodity flows perturbations. The authors assert that this arises from (1) as a critical transfer facility, ports are particularly susceptible to disruptions in commodity flows that can lead to cargo losses and further cascading effects across industries and regions, and (2) commodity import and export data are easier to be estimated or obtained in the case of ports. For example, Zhang et al. [5]

[1] Here by linear calculation refers to calculations based on simple multiplication based on transportation disturbance indicators (such as increased travel times) and monetized generalized costs per unit.

investigated the economic losses of port disruptions based on a linear calculation, which includes reputational loss, loss to the shippers, loss to the carriers, and loss to the ports. Zhang and Lam calculated the direct losses and losses due to delay of import and export commodities for four simple supply chain disruption cases in the Shenzhen Port disruption scenario [7,23]. In these studies, ripple effects such as supply chain disruptions across the whole economy are not taken into account. Few researchers leveraged advanced economic approaches such as Input-Output (I–O) models to assess the ripple effects of port disruptions. For example, Pant et al. calculated the indirect economic impacts of export and import losses due to port closure of the Port of Catoosa in Oklahoma based on a risk-based Multi-Regional Inoperability Input-Output Model [6]. Possible substitutions between transportation modes and facilities are not captured in this case. Park et al. studied the substitution effects of periodic changes, port changes, and modal changes under port shutdown scenarios based on a multi-regional Input-Output model named NIEMO [24]. However, the inherent shortcomings of the I–O models such as the missing scope for factor substitutions and fixed coefficients still exist.

In addition, disruptions of other transportation modes such as waterways were also studied [8,25,26]. Some researchers investigated the social-economic impacts of transportation disruptions due to construction projects in urban areas [27,28], as the functionality of the transportation system can be affected due to these activities. The impacts are considered localized if no critical linkages are affected. Many researchers focused on road transportation disruptions, given the importance of road transportation for the mobility of goods and people, which will be discussed in detail in the following sections.

2.2. Scale of economic impacts

Some researchers focused on the evaluation of partial economic impacts caused by the disruptions of critical transportation facilities through single or multiple supply chain(s). For example, Lewis et al. [29] quantified the cost for an individual firm operating a global supply chain in face of a hypothetical temporary closure of a container seaport. Gueler et al. [8] compared the delivery costs of the coal supply chain for the energy generation industry under different Ohio River disruption scenarios and identified critical locks, the best alternative coal supply points, and transportation modes. Paul et al. [9] investigated the recovery planning in a simple-structure supply chain caused by sudden transportation disruptions with costs of delivery delay and quantity losses into account. The scale of the economic impacts investigated within these studies are limited to the monetary losses in imports and exports of commodities, delivery and storage costs, as well as the upstream and downstream cascading impacts through supply chain(s). Economic impact analysis models such as I–O and CGE models were not leveraged and other indirect impacts such as price perturbations are not captured in their models. This can be related to the objectives of this type of research which are to help stakeholders and managers to identify critical nodes and mitigate possible losses under transportation disruptions [8,9]. Other researchers focused on the wide indirect economic impacts caused by transportation disruptions, which will be discussed in detail in the following subsections. It needs to be noted that our research highlights the important role of transportation systems and its connections to the economic system. Therefore, some studies such as those focusing on the investigation of the economic impacts based on aggregated sectoral output reductions or productivity losses [30,31] are not included in the literature review.

2.3. Types of transportation flow and the indirect economic impacts

In most traditional macroeconomic models such as I–O models, CGE models, etc., transportation services are treated in similar ways to other production industries or as trade margins that are added to commodity prices, while the physical networked nature of transportation infrastructure systems is ignored. Another important challenge in this area is that the characteristics of transportation modeling at different scales such as the origins and destinations at the trip level or total travel times, distances, and average speeds at the network level are not fully captured in economic models. Because of these missing connections between these two types of models, researchers working across these disciplines to assess the (indirect) economic impacts of transportation disruptions usually introduced the direct losses of transportation sectors into macroeconomic models as a single shock [32,33], ignoring the complex nature of transportation systems and transportation activities as well as the linkage between those and economic activities. These kinds of measurements can lead to uncertainty in the estimated results when the complex connections between transportation sectors and other types of economic activities (i.e. production and consumption) are oversimplified.

In this context, researchers tried to develop integrated frameworks that combine transportation systems analysis with economic approaches, as well as other modules such as hazard simulations and damage assessments. Efforts have been taken in order to construct linkages between models from different domains and provide more accurate analyses of transportation disruptions. In the economic analysis part, commodity flow perturbations and passenger flow perturbations are treated separately, given that freight transport and passenger trips correspond to different types of impacts on the economy. The impact of commodity flow perturbations is more straightforward. For example, goods and materials are transported from origins to destinations by trucks for sales during which transportation costs are added into the prices as trade margins. As a result, price perturbations caused by changes in transportation costs affect the competitiveness of industries and regions causing ripple effects across the economy. On the other hand, passenger transportation can be divided by the purpose of trips, for instance, business trips and leisure trips [34,35], which can demonstrate a spectrum of responses to a transportation disruption and thus have different impacts on the economy. Worse still, estimation of economic impacts caused by passenger flow perturbations is considered more challenging due to the scarcity of data [36] and the lack of methodological linkages relating passenger flow perturbations to economic activities.

With regards to the economic impacts caused by commodity flow perturbations, Kim et al. [37,38] assessed the shipment costs changes for different modes of transport caused by transportation network disruptions by combining a transportation network model and a regional commodity flow model incorporated with input-output relationships. Vadali et al. [39] calculated the transportation-related costs of critical ports-of-entry (POEs) and bridge failure in bi-national regions. Oztanriseven and Nachtmann [25] calculated the disruption costs of inland waterway disruption by linearly summing up the transportation cost, holding cost, and penalty cost. In the case of the economic impacts caused by passenger flow perturbations, Postance et al. [3] investigated the social-economic losses of passenger flow perturbations under road transportation network disruption caused by landslides in Scotland. Landslide hazard information and an integrated micro-meso scale traffic simulation model were used. However, the economic impacts were derived by multiplying travel time changes with generalized costs (i.e. the market price value of occupant time and vehicle operation), without considering the further ripple effects caused by increased travel time on the economic system. Few researchers estimated the economic impacts of both commodity flow perturbations and passenger flow perturbations. Mesa-Arango et al. [40] estimated the transportation-related costs due to highway network disruption caused by floods. Bardal and Mathisen [41] designed a model to estimate the economic costs caused by unexpected road traffic disruptions, based on values of increased travel time and other costs, then applied it to a specific road section in the northern part of Norway. However, indirect economic impacts caused by transportation costs perturbations across the whole economic system were not captured in the aforementioned research.

A number of studies leveraged I–O models and CGE models to investigate the indirect economic impacts caused by transportation perturbations. Cho et al. [36] calculated the state-level indirect economic impacts due to commodity shipping costs changes for critical bridges and tunnels disruption scenarios based on an integrated framework with a multi-regional Input-Output model named NIEMO and national highway network model. Wei et al. [12,13] simulated the regional indirect economic impacts caused by commuting costs increase based on an interdisciplinary framework with integrated I–O models, disaster simulations and transportation network modeling. Darayi et al. [42] investigated the impacts of multi-modal freight transportation disruptions based on a modified Inoperability Input-Output model in order to devise contingent rerouting plans to strengthen the network's adaptive capacity. Moreover, Kim and Kwon [43] estimated the indirect economic impacts caused by disrupted accessibility for commodities under assumed nuclear power plant accidents based on a Spatial Computable General Equilibrium (SCGE) model. In a report prepared for the Ministry of Transportation in New Zealand, the indirect economic impacts caused by transport margins increased due to transportation network disruptions caused by the 2016 Kaikoura Earthquake were investigated [10]. In these examples of research, only one kind of flow and its perturbations were analyzed and the interactions between passenger flow and freight flow were neglected due to missing passenger trips information.

Few researchers took both freight transportation and passenger transportation perturbations into account and estimated the more comprehensive indirect economic impacts. Cho et al. [44] investigated the economic impacts of the Elysian Park Earthquake and transportation disruptions based on an integrated framework combining bridge structure performance model, transportation network model, and I–O model. Four classes of freight flows and nine classes of passenger trip types were considered in their simulations. However, limited indirect economic impacts were calculated due to the inherent limitations of I–O models, which led to authors overlooking the effects of price adjustments across the economic system. For example, transportation costs perturbations can lead to household demand changes. Tirasirichai and Enke [11,45] brought leisure time into the labor endowment constraint of the household and estimated the indirect economic impacts of highway bridge damage based on earthquake impact analysis results [46], transportation network modeling, and regional CGE model. However, the authors incorporated transportation shocks into the economic model as increased production cost (or decreased production efficiency) in the truck transportation sector for freight flow perturbations while transportation costs are taken as normal production input costs, which is not completely consistent with the reality. For instance, some transportation costs are added into commodities' prices as trade margins, instead of intermediate production costs when these commodities are transported from produced sites to final demand users. In addition, the changed costs due to changes in passenger travel distances were directly introduced into the CGE model as capital endowment increases, which is inconsistent with the reality where changed transportation costs will affect household consumption behaviors under budget constraints instead of leading to increasing capital for households. Tatano and Tsuchiya [4] applied SCGE models to estimate the indirect economic impacts caused by the transportation network disruption after the Niigata-Chuetsu Earthquake in 2004. Physical damages of transportation infrastructure were not included in their process. In addition, the iceberg formulation of transportation costs was assumed for trading production, which treats evaporation of products as a transportation cost without specific linkages to transportation industries. This can cause uncertainty in estimating the total economic impacts as truck transportation perturbations will lead to increased or decreased demands for various kinds of commodities or services along the supply chains. For instance, extended transit time for trucks will cause extra labor inputs for delivering the same amount of commodities. Other operation costs such as fuel costs and vehicle maintenance costs also need to be considered.

Considering the aforementioned gaps in the literature, the authors assert that a comprehensive estimation of the economic impacts caused by transportation disruptions needs to be achieved to support a more informed decision-making process aiming at reducing economic losses and acting upon mitigation and resilience measures. To do this, integration of transportation simulation results that are generated by engineering models into the economic models that can simulate the interdependency of transportation activities and other industries in the economy needs to be done. In addition, indirect economic impacts caused by damages to infrastructure, direct business interruptions and transportation flows perturbations need to be assessed based on advanced economic models. Both commodity flow perturbations and passenger flow perturbations should be considered in this process. Finally, linkages between the analyses of the transportation system and the economic impact should be devised carefully to capture the holistic impacts of transportation disruptions.

3. The proposed framework

A multidisciplinary framework is proposed to provide a comprehensive estimation of the indirect economic impacts of transportation disruptions. In this framework, hazard simulation results indicating physical damage, perturbations in transportation flows, and other related costs from cutting-edge data inventories and simulation procedures as well as explicit transportation network modeling are integrated with the CGE model. A wide range of data needs to conduct an estimation of indirect economic impacts are identified as well. It needs to be noted that the authors are taking road network disruptions caused by an earthquake scenario as an example to demonstrate the workings of the framework through a case study, yet this should not limit the generalizability of the proposed framework to other cases if data availability is assured.

Due to existing methodological gaps between transportation network modeling and economic modeling, efforts were taken for the convergence of the two kinds of models by the development of special linkages. Given that one of the most important variables in CGE models is the price, and it is straightforward to relate monetary costs to transportation-related activities such as gasoline costs, vehicle maintenance costs, transportation ticket fees, and so on (through the perspective of consumption), this framework firstly converts transportation perturbations into monetary costs. It is widely acknowledged that hazard-induced transportation system disruptions can cause a surge in travel times and travel distances [21]. Consequently, transportation costs increase due to such decreases in network functionality. Tracing these costs and their impacts on the economic system through CGE modeling, upstream and downstream cascading impacts generated through supply chains and price perturbations can be captured. In addition, damages to general building stock as well as business income losses caused by disasters can be obtained by using HAZUS [16] (an open-source FEMA software commonly used for multi-hazard simulations) based on systematic hazard analysis and loss assessment methodologies. In the framework, physical damages (including structural and non-structural building and infrastructure damages) and losses of contents of buildings (such as office equipment and furnishings) are modeled as capital stock reductions, which will impact the economy through factor substitutions and price perturbations. Further, the indirect economic impacts caused by business interruptions are simulated through industry output reductions. The authors discussed hazard characterization, damage assessment as well as transportation system analysis in detail in their earlier work [21].

In the proposed framework, The Enormous Regional Model (TERM) was employed to conduct the CGE simulations, given the advantages provided by its detailed database as well as its model structure. The TERM model is a static multi-regional CGE model with a high degree of regional details, developed by the Centre of Policy Studies at Victoria University [47]. As a CGE model, TERM overcomes many limitations of I–O models such as linearity, lack of substitution possibilities and resource constraints, and lack of price-response behavioral content. Apart from that, the TERM model has a well-extended sector structure and regional detail as well as a well-constructed database which was developed based on detailed official national and regional statistics. For instance, in the TERM model, trade matrices are constructed based on regional and inter-regional trade data, which contains information about sources (i.e., imported or domestic), origins, and destinations of commodities. In addition, the TERM model provides a more detailed treatment of transport margins, compared to other multi-regional economic models such as the GTAP model [48]. In the TERM model, the costs of those transportation products and services that are used during production are taken as intermediate input costs, while other transportation costs are included in the trade margin matrices, which record the value of any trade or transport services used to deliver commodities from their production sites to the final users [48]. This brings convenience to the investigation of the indirect economic impacts caused by freight flow transportation perturbations.

Changes in transportation costs due to transportation perturbations are calculated in the following ways. Costs arising from increased travel distances are calculated according to vehicle-based operating costs and ownership costs, such as fuel costs, repair and maintenance fees, tires, tolls, permits and license fees, insurance premiums, and vehicle lease or purchase payments, with respect to changes in the distances of travel. Based on these costs, the indirect economic impacts due to travel distance changes can be simulated.[2] For increased travel times, the approach depends on the type of flow. For freight flows, costs are estimated based on labor costs in the transportation sectors such as driver wages and driver benefits. For passenger flows, because CGE models do not take time as one of the endowments like labor, capital, land, etc., a direct link between increased travel times and economic costs is not available. It is then necessary to first translate the increased travel times into monetary values. Given that researchers and institutions have been calculating the monetary costs of increased travel time for passenger flows based on the Value of Travel Time (VOT), or the Value of Travel Time Savings (VTTS), which provides a general evaluation of passenger travel times under different conditions (transportation mode, travel distances, income levels, etc.) [49,50], this study uses averaged values of travel time to represent the monetary costs due to increased travel times. Then in the CGE modeling, the increased costs due to passengers' increased travel times are simulated as reduced efficiency of labor endowment used during the production process, based on the assumption that increasing travel time (i.e. extra time spent for commuting) will affect the production efficiency of workers [51,52]. It also needs to be mentioned that, in this study, we assume that people will retain their travel demand after the initial shock of the disruption-causing event and throughout recovery.

All identified direct impacts caused by transportation infrastructure disruptions are put into the TERM model as external shocks through a series of "CGE drivers", i.e. values that can be input into CGE models [53]. Changes in freight transportation costs due to increased travel distances can be simulated by adjusting trade margin variables which in turn affect the delivered prices of commodities and services (see "Model Linkage a" in Fig. 1). The increased costs caused by increased travel times of freight flow are introduced into the TERM model as shocks to the technical efficiency parameters of labor factor usage for transportation sectors (see "Model Linkage b" in Fig. 1). Changes in household consumptions caused by passenger flow perturbations are integrated into the TERM model through shocks to the technical efficiency of labor used for production and shocks to the variables associated with

[2] For freight flow, changes in transportation costs can be directly related to transportation margin cost, which is a part of the price of commodity/service. For passenger flow, changes in transportation costs can lead to household consumption preference changes. In this study, the authors only consider the percentage changes of household consumptions on travel-related commodities (such as petrol) due to transportation disruptions. Other possible household consumption preference changes (such as panic buying) are not included to due lack of data.

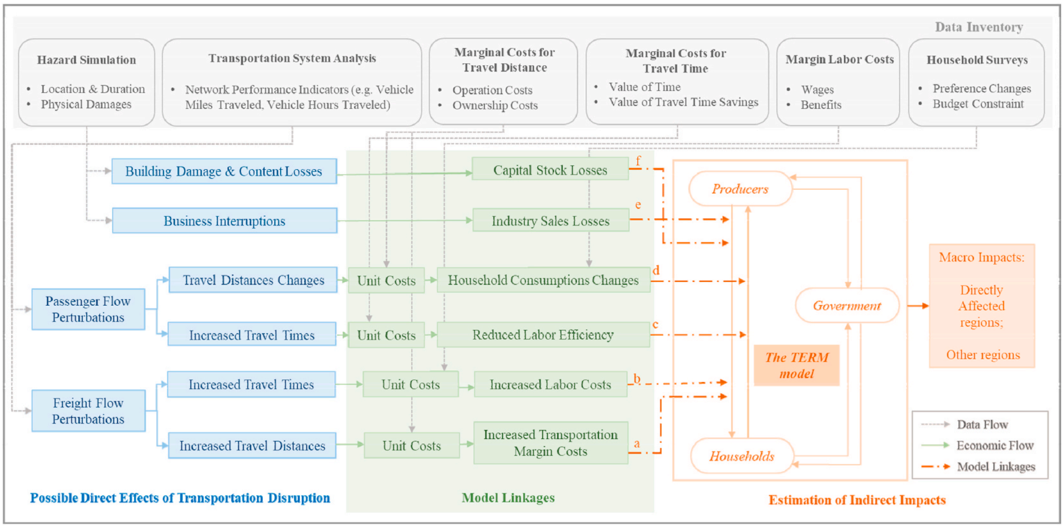

Fig. 1. Framework illustrating the linkages between hazard and transportation disruption indicators, and the CGE model.

household consumption preferences (see “Model Linkages c and d” in Fig. 1). In addition, the indirect economic impacts caused by physical damages to buildings and business interruptions are estimated by capital usage variables and industry output levels in TERM models, respectively (see “Model Linkages f and Linkage e” in Fig. 1). Based on these “CGE drivers”, the indirect economic impacts of transportation disruptions can be estimated, and further investigation can be carried out by evaluating more detailed results such as the distribution of output losses across industries and regions, impacts on employment and changes in prices of goods and services, etc.

During the development of methodologies for assessing the total economic impacts, double counting can be one of the pitfalls that need to be avoided [54]. As a result, measures need to be taken to avoid double-counting issues during indirect economic impacts evaluation. For example, caution needs to be taken when implementing multiple external shocks into CGE models, given that double counting could happen if the same loss item was attributed to multiple entities [55]. An example of this aspect has been provided by Rose [55], “… *as in the case of avoiding counting retail store sales as a loss to both the storeowner and its customer*”. In addition, double counting can happen if all of the attributes of some goods and services were set at their maximum levels at the same time, which is not possible in reality [55]. Existing approaches to avoiding double counting include: subtracting double-counted values when the same source of impact is investigated from both the demand-side and supply-side [56,57], applying the largest production input constraint only on the supply-side [58], taking the value-added loss as the decreased production loss [59], and avoiding to take capital stock shocks and capital input supply shocks at the same time when simulating the impacts of production loss [60].

Apart from that, it is widely debated whether it is suitable to add up the stock loss and the flow loss to represent the total economic impacts [54,55,61]. Mechler [62] revealed the underlying assumption of the arguments against adding the direct and indirect losses up, which is that “*all direct and indirect impacts can be assessed and the cost concept used for valuing asset losses is that of the book value (purchase value less depreciation), which are not realistic assumptions for disaster impact assessment*”. For damaged property, Rose [55] supported the idea of adding the stock and flow loss in an appropriate way, if the flow loss measures the opportunity costs of delays during recovery.

However, subtracting the double-counted values can be tricky given the scenario complexity and the variance and inconsistency among various data sources. For example, businesses such as shops and restaurants can be affected for various reasons. If a restaurant is closed due to extensive physical damage or total building loss after an earthquake, consumers would cancel their trips to the restaurant or choose another place to eat, and there would be no demand for food and other ingredients from this restaurant to upstream industries. In this case, extra costs due to passenger flow and freight flow perturbations will no longer exist. However, if a restaurant is affected because one of the few critical bridges to access this restaurant is damaged, extra time or distance will be experienced by both consumers who attend the restaurant and the truck drivers serving this restaurant’s supply chain. In this case, the increased transportation costs due to transportation perturbations need to be accounted for the evaluation of the indirect economic impacts. To sum up, potential double counting can still exist if the initial data are collected from multiple sources and cannot be easily distinguished in complicated settings. The analyst needs to be flexible for such scenarios and in handling various data sources.

Although impacts from both building damages and content losses, as well as business interruptions, are included in the framework, caution needs to be taken to estimate the total indirect economic losses, given the potential double counting issue when both capital stock losses and output reductions for producing sectors are simulated concurrently. The significance of this issue depends on the characteristics of the producing sector. For example, for service sectors with fewer capital inputs (such as food delivery), potential double counting can be minimal and ignorable. To the contrary, for industries with big plants and heavy machines, adding up the indirect economic losses caused by capital stock damage and business interruptions may affect the reliability of the final results. Nevertheless, including both the impacts stemming from capital stock losses and business interruptions provides an upper bound of potential economic impacts caused by transportation disruptions.

4. Case study

4.1. An overview of the scenario and the sources of data

A case study was conducted to validate the proposed framework. In order to provide a comprehensive estimation of the indirect economic impacts caused by transportation disruptions and disasters, simulation results of transportation flow perturbations from Koc et al. [63] were used. Koc et al. [63] employed a synergetic system-based approach that connects seismic hazard analysis with transportation network analysis which was employed in a Greater Los Angeles Area case study to investigate the impacts of a 7.3 M scenario earthquake. In their study, only road network disruptions were simulated and the interactions between road transportation and other modes were not captured. Downtime estimate for each bridge in the study region was analyzed using HAZUS based on a hybrid inventory (partially from image-based models) and explicit road transportation network models were constructed to investigate the transportation perturbations. Six network versions in total (for days 0, 1, 7, 30, 90, and 104 after the scenario earthquake) were simulated under fixed travel demand assumption to quantify the disruption and recovery of transportation in the region. The results were aggregated to the county-level of detail. Based on this, the percentages of building/content damages were calculated for the 3-county Los Angeles Metro Region by Wei et al. [64]. Areas outside the study region (the L.A. Metropolitan Area) were shown to be minimally impacted by the hazard, thus the economic analysis does not account for building or content losses outside said region. The authors assumed that all freight transportation trips were made by trucks, and all passenger trips were made by private vehicles.

In general, the scenario earthquake causes severe physical damage, business income losses as well as transportation perturbations in the study region. The building and content losses of the Los Angeles County, the Riverside County, and the Orange County are evaluated as $33,997.64, $5790.51, and $293.11 million US dollars which correspond to 3.00%, 1.47%, and 0.12% of their total exposure values, respectively. Apart from that, a $1276.71 million US dollars income loss[3] is expected for the study region in total. Furthermore, the transportation network functionality of the Greater Los Angeles Area would be severely damaged, with 137 bridges closures on Day 1 after the earthquake resulting in 850,000 additional hours spent in traffic (Fig. 2). It takes 105 days in total for the road transportation network to recover to the pre-disaster functionality level. Overall during the disruption (recovery) period, an additional 11,836,497 h for personal trips and 1,151,973 h for freight delivery are spent in traffic. 10,491,196 additional miles would be taken by truck drivers in the study region during the same period. Within the study region, Los Angeles County experiences most of the transportation system functionality loss. Detailed information for transportation disruptions can be found in Ref. [63].

In this study, a customized TERM database is used, which contains 4 aggregated regions and 97 economic sectors [47]. The 4 aggregated regions are the Los Angeles Metropolitan Region (hereinafter called the LA Metro Region), the San Francisco Metropolitan Region (hereinafter called the SF Metro Region), the Rest of California, and the Rest of U.S. Given that the aim of this case study is to show the feasibility of the framework for the estimation of wide indirect economic impacts caused by transportation perturbations, this customized database is eligible because it can provide adequate support to the TERM to simulate the regional economic impacts in each sub-region of California, and the spatial substitution effects among these sub-regions and the rest of the U.S. in the process.

Given that the benchmark year for transportation network simulations is 2016, unit values in 2016 U S. dollars are taken to evaluate the transportation costs changes and the indirect economic impacts. It needs to be pointed out that the TERM model is adapted to the U. S. on the basis of regional input-output data for the year 2010. Given that external shocks are introduced into the TERM model in percentage forms, the authors try to eliminate the influence of inflation in the simulations. Estimated transportation costs change based on transportation perturbations data and unit values are first adjusted to 2010 U S. dollar values and then divided by the corresponding total value, if the corresponding total value is taken from the TERM database. If the corresponding total values are in 2016 U S. dollars, for example, the value of regional employment compensations obtained by IMPLAN [65], no extra adjustment needs to be done. All simulations are conducted based on a short-run closure rule on an annual basis, under which household consumption, usage of capital and land are treated exogenously and employment is adjusted endogenously.

4.2. The economic impact of freight flow perturbations

Due to the scarcity of information about transportation perturbations under dynamic recovery scenarios, the assumption of linear recovery of transportation network functionality in each interval of time for 6 representative network versions is made [21]. Perturbations of freight flows are estimated in terms of the Vehicle Hours Traveled (VHT) and the Vehicle Miles Traveled (VMT). Increased transportation costs are calculated by multiplying their differences (compared to previous situations) with unit labor cost and unit operation cost, respectively. The unit labor cost of truck drivers is calculated by averaging truck driver wages from the literature. The national mean hourly wage for heavy and tractor-trailer truck drivers is reported to be $20.96 in 2016 by the U.S. Bureau of Labor Statistics [66]. The American Transportation Research Institute estimates the marginal costs for driver wages are $20.91/h without driver benefits, and $27.09/h with benefits [67]. The statewide average travel time parameter suggested by the Caltrans is $31.40/h for economic analysis [68]. Averaging these values together gives $25.09/h for truck drivers.

The unit operation cost of truck drivers is estimated similarly. The American Transportation Research Institute (ATRI) estimates the vehicle-based marginal fuel cost and non-fuel costs (including lease or purchases payments, repair and maintenance, insurance, permits and licenses, tires and tolls costs) are $0.577 and 0.336 per mile, respectively [67]. The California statewide average non-fuel costs for trucks are suggested to be $0.429 per mile in 2016 U S. dollars [68]. In addition, Boyer estimates $0.2 per mile for fuel cost and $0.4 per mile as non-fuel costs for truck depreciation, licensing, interest, tires, and maintenance costs in 1997 [69]. According to

[3] According to HAZUS technical manual, income loss takes place when economic activities were interrupted due to building damage. The income loss are estimated based on pre-disaster income level, building floor area, disruption duration, and production recapture variable etc.

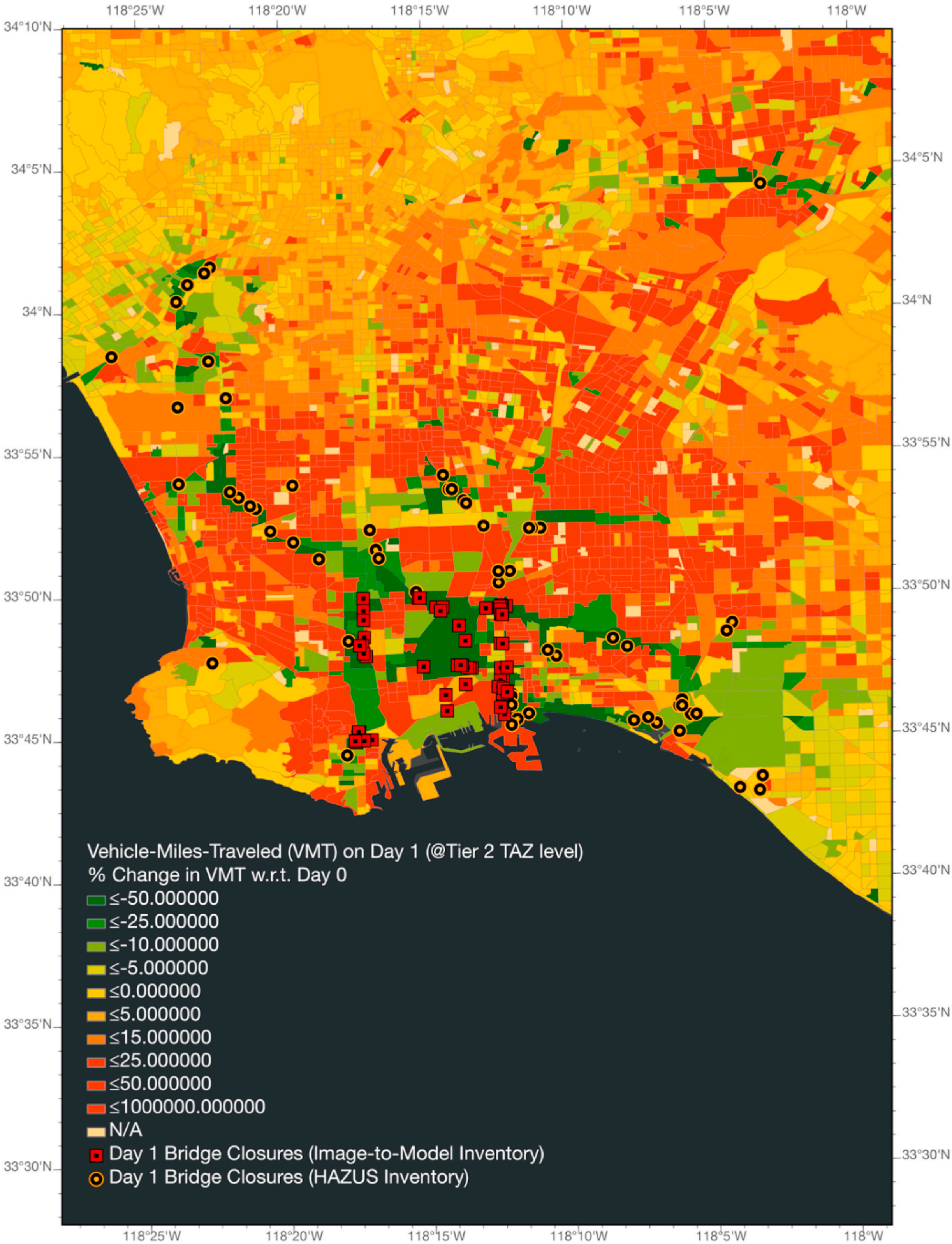

Fig. 2. Bridge closures and transportation perturbations on Day 1 after the earthquake. Figure was reprinted with Elsevier permission from Koc et al. [21] based on data from seismic hazard simulation and explicit transportation network modeling.

an operation costs study conducted by researchers at the University of Minnesota [70], the average non-fuel costs for commercial trucks under three different road conditions are $0.25 per mile in 2003 U S. dollar value, and the average fuel cost is $0.236 per mile with fuel price of $1.50 per gallon.[4] Averaging these values together gives $0.85 per mile for truck operation costs.[5]

The indirect economic impacts of freight flow perturbations are simulated based on shocks implemented through variables "***alab_o***" and "***atradmar***" in the TERM model, which influence the economy by labor factor usage and transportation trade margin cost, respectively. The indirect economic impacts caused by increases in truck transportation costs are presented in Table 1. For the integrated impacts of increases in truck transportation costs, both shocks on labor factor and transportation trade margin are taken into consideration.

The L.A. Metro Area experiences over 56 million dollars in losses due to increases in truck transportation costs. The potential effects of increases in labor costs outnumber that of increases in operation costs in the L.A. Metro Area. And the indirect impacts caused by freight flow perturbations due to transportation disruption are mostly concentrated within the L.A. Metro Area. This is because that the disruption scenario only lasts for a short period and most of the perturbations concentrate within the L.A. Metro Area. Given that a large part of the truck transportation services in the directly affected region is locally generated and consumed, the concentration of indirect economic impacts caused by freight flow perturbations is reasonable. Additionally, transportation disruption in the L.A. Metro Area can have positive impacts on other regions because of substitution effects (i.e., inter-regional shifts of economic activities). This can be validated by the increases in the total output level of the *Truck Transport* sector in the S.F. Metro Area and the Rest of California. In total, freight flow perturbations lead to 53.07 million dollars GDP losses for the U.S.

4.3. The economic impact of passenger flow perturbations

Similar to freight flow perturbations, perturbations of passenger flows are estimated based on VHT and VMT. One interesting result of Koc et al. [21] is that due to the high redundancy of the road network in densely populated areas of Los Angeles, the disrupted highway traffic flows diverting onto the street network (away from the freeways where most of the bridge damage occurs) results in a decrease in average VMT. This can be explained by travelers having to resort to shorter distance but longer duration routes, i.e., routes traversing streets instead of freeways. Similar results can be found in other previous studies, for example in the St. Louis Metropolitan Area study investigating the impacts of simulated earthquake events [45].

According to the American Automobile Association (AAA), the average driving cost is $0.57 per mile (assuming 15,000 total miles per year), including gas, maintenance, tires, insurance, license and registration fees, taxes, depreciation, and financial charges [71]. In addition, the non-fuel cost in California for automobiles is suggested to be $0.313 per mile, and the regular unleaded fuel price is $3.18 per gallon in 2016 [68]. So the average fuel cost is $0.14 per mile based on the average light-duty vehicle fuel efficiency provided by the Bureau of Transportation Statistics [72]. Besides, based on the investigation conducted by researchers from the University of Minnesota [70], the average fuel costs for automobile and pickup/van/SUV are $0.057 per mile and $0.086 per mile, respectively, with a fuel price of $1.50 per gallon.[6] These average fuel costs are adjusted according to the fuel price level in California. And the average non-fuel costs (including maintenance, repair, tires, and depreciation) for automobiles and pickup/van/SUV under different road conditions are $0.12 per mile and $0.13 per mile in 2003 U S. dollars, respectively [70]. Based on these values, the authors use an average unit operation cost for passenger trips of $0.448 per mile.

For the value of passenger travel time, the U.S. Department of Transportation recommended $14.1 per person-hour in 2015 U S. dollars as the Value of Travel Time Savings for all travel purposes [49]. Caltrans suggests $13.65 per person-hour as the Value of Time for transportation economic analysis [68]. In this way, the average value of travel time is set as $13.96 in this case.[7]

Then the indirect economic impacts of passenger flow perturbations are simulated based on shocks implemented through variables "***alab_o***" and "***ahou_s***" in the TERM models, which influence the economy by labor factor usage and household consumption preferences, respectively. The indirect economic impacts caused by passenger transportation perturbations are presented in Table 2. In total, the LA Metro Area has over 270 million U.S. dollars in losses due to increases in passenger transportation costs.

4.4. The economic impacts of building damage, content losses and business interruptions

The authors calculated the annual buildings and contents loss ratio based on the HAZUS simulation results, following the methodology of Wei et al. [64] described in their research report that investigated the effectiveness of resilience tactics under transportation infrastructure disruptions. The annually averaged loss percentages are put into the TERM model as the capital stock damages through the variable "***xcap***", which denotes the physical capital supply for production by industry and by region. The indirect economic impacts of Row (1) shown in Table 3 are the total indirect impacts for all industries due to capital stock losses caused by the earthquake (without mitigation and resilience measures). Similarly, business income loss ratios are calculated based on the business income losses generated by the HAZUS software for the given earthquake scenario. After that, these ratios are introduced into the TERM model as reductions in industry output through the variable "***atot***", which indicates a technical change that will affect the industry output level. The indirect economic impacts of Row (2) shown in Table 3 are the total indirect impacts due to business interruptions in all sectors

[4] This fuel cost value is adjusted to $0.472 per mile during calculating the average unit operation cost for truck transport, according to the suggested fuel cost provided by Caltrans [68], which is $3 per gallon.

[5] Inflation has been taken in order to make sure each unit value is in U.S. 2016-dollar value.

[6] The fuel cost values are adjusted to $0.120 per mile and $0.182 per mile during calculating the average unit operation cost for truck transport, according to the suggested regular unleaded fuel price for automobile provided by Caltrans [68], which is $3.18 per gallon.

[7] Inflation has been taken in order to make sure each unit value is in U.S. 2016 dollar value.

Table 1
Real GDP Impacts of Increases in Truck Transportation Costs(Million U.S. dollars and percentage losses from pre-disaster levels).

		LA Metro Region	SF Metro Region	Rest of California	Rest of US	US Total
(1) Impacts of increases in truck transportation costs (distance)	GDP Losses	−22.48	0.09	0.78	4.10	−18.04
	(%)	−0.002355	0.000012	0.000100	0.000027	−0.000102
(2) Impacts of increases in truck transportation costs (travel time)	GDP Losses	−33.51	−2.02	0.97	0.00	−35.02
	(%)	−0.003511	−0.000262	0.000125	0.000000	−0.000198
(3) Integrated impacts of (1) and (2)[a]	GDP Losses	−56.03	−1.92	1.76	4.10	−53.07
	(%)	−0.005871	−0.000250	0.000226	0.000027	−0.000300

[a] It is noteworthy that due to the non-linearity of the CGE model, the integrated impacts may not equal to the sum of two individual simulations. The same applies to Tables 2 and 3.

Table 2
Real GDP Impacts of Increases in Passenger Transportation Costs (Million U.S. dollars and percentage losses from pre-disaster levels).

		LA Metro Region	SF Metro Region	Rest of California	Rest of US	US Total
(1) Impacts of changes in passenger transportation costs (distance)	GDP Losses	−10.94	0.10	0.28	5.16	−5.66
	(%)	−0.001146	0.000013	0.000036	0.000034	−0.000032
(2) Impacts of increases in passenger transportation costs (travel time)	GDP Losses	−261.29	4.53	0.99	50.42	−211.56
	(%)	−0.027378	0.000589	0.000128	0.000332	−0.001196
(3) Integrated impacts of (1) and (2)	GDP Losses	−272.23	4.64	1.27	55.59	−217.22
	(%)	−0.028524	0.000603	0.000164	0.000366	−0.001228

affected by the earthquake.

It needs to be mentioned that HAZUS has a highly aggregated industry structure compared to the TERM model. Further, there is no sufficient data to break down losses estimated at the level of HAZUS industries into refined industry-level losses that are consistent with the TERM model database. In this case, the authors follow Wei et al. [64] and match the buildings and contents loss ratio of a single industry generated by HAZUS to multiple industries in the TERM model. The authors follow the same approach to match business income losses generated by HAZUS with corresponding industries in the TERM model. In this way, the authors calculate the indirect economic impacts caused by buildings and content losses, and business interruptions of all sectors under the earthquake scenario, which to some extent can explain why the results of Row (1) and (2) in Table 3 are much higher than losses in Tables 1 and 2. To take a close look at the indirect economic impacts caused by physical damage and business interruptions in transportation sectors, the authors consider scenarios in which only road transportation infrastructure service sectors are directly affected by the earthquake, according to the percentage loss ratios generated by HAZUS. The LA Metro Region suffers about 144.24 million U.S. dollars in GDP losses due to buildings and content losses in the *Truck Transport* and *Transit and the Ground Passenger Transport* sectors caused by the earthquake (see Row (3)). The LA Metro Region has about 16.78 million dollars in GDP losses due to business interruptions in the *Truck Transport* and *Transit and Ground Passenger Transport* sectors (see Row (4)). Row (5) shows the integrated impacts of capital stock losses and business interruptions in the *Truck Transport* and the *Transit and Ground Passenger Transport* sectors. It needs to be mentioned that given the potential double counting issue as explained in Section 3, results in Row (5) can be considered as the upper bound estimates of indirect economic impacts caused by capital stock losses and business interruptions in the two road-transportation-related sectors.[8]

5. Discussion and limitation

The authors do not provide a total indirect impacts number in the case study. This is due to the aspect that the earthquake scenario used in the case study can cause massive destructive physical damages with potentially huge indirect economic impacts that are not directly related to transportation disruptions. For example, damages to electric power plants and their indirect economic impacts are out of the scope presented here. In other words, results in the first two rows of Table 3 indicate the general economic impacts caused by all types of building and content losses resulting from the earthquake while Tables 1 and 2 only show the economic impacts of transportation disruptions. Moreover, given the distinct difference in the industry aggregation resolutions of HAZUS and the TERM

[8] There are three kinds of endowment included in the TERM model as production inputs, namely capital, labor and land. Row (3) of Table 3 only indicates the indirect economic impacts due to capital stock losses. Although capital stock damage can be part of the reason for business interruptions for some industries, there are other factors that can lead to business interruptions and eventually lead to widespread indirect economic impacts, for instance, sales losses for grocery stores due to lack of staff after transportation disruptions. In such case, actual economic impacts will be higher than Row (3) but lower than Row (5). Unfortunately, further exclusion of double-counted parts cannot be achieved based on the existing HAZUS simulation results used in this case study.

Table 3
Real GDP Impacts of Building and Content Damages and Business Interruptions (Million U.S. dollars and percentage losses from pre-disaster levels).

		LA Metro Region	SF Metro Region	Rest of California	Rest of US	US Total
(1) Indirect economic impacts caused by building and content losses in all sectors	GDP Losses	−26,690.92	101.83	−232.97	2513.76	−25,274.06
	(%)	−2.796639	0.013226	−0.029998	0.016551	−0.142881
(2) Indirect economic impacts caused by business interruptions in all sectors	GDP Losses	−5653.88	31.94	−20.44	397.01	−5381.67
	(%)	−0.592406	0.004149	−0.002632	0.002614	−0.030424
(3) Indirect economic impacts caused by building and content losses in the *Truck Transport* and the *Transit and Ground Passenger Transport* sectors	GDP Losses	−144.24	−6.77	3.67	10.33	−138.86
	(%)	−0.015113	−0.000879	0.000472	0.000068	−0.000785
(4) Indirect economic impacts caused by business interruptions in the *Truck Transport* and the *Transit and Ground Passenger Transport* sectors	GDP Losses	−16.78	−0.22	0.24	2.73	−14.33
	(%)	−0.001758	−0.000029	0.000031	0.000018	−0.000081
(5) Integrated impacts of (3)+(4)	GDP Losses	−161.01	−7.00	3.91	13.06	−153.19
	(%)	−0.016870	−0.000909	0.000503	0.000086	−0.000866

* Note: The *Truck Transport* and the *Transit and Ground Passenger Transport* sectors are the only two sectors directly related to road transportation infrastructure services in the TERM model database used in this paper.

model, some physical capital loss (including building damage and content loss) ratios were used repeatedly for many sectors in the TERM model which can lead to the overestimation of the indirect economic impacts caused by buildings and contents losses. This means that the indirect economic impacts caused by transportation flow perturbations are not directly comparable to the indirect economic impacts caused by damages to all types of buildings and content losses.

In this case, the authors estimate the indirect economic impacts caused by physical capital loss as well as business interruptions for the *Truck Transport* sector and the *Transit and Ground Passenger Transport* sector, which are the only two sectors directly related to road transportation among 97 sectors in the TERM model. Results show that for the LA metro region, the indirect economic impacts caused by physical capital loss and business interruption are 144.24 and 16.78 million U.S. dollars in GDP loss, respectively. But the indirect economic impacts caused by freight flow and passenger flow perturbations due to transportation disruption are 56.03 and 272.23 million U.S. dollars in GDP loss, respectively. The results of the case study show that the indirect economic impacts caused by passenger flow perturbations and freight flow perturbations are large demonstrating the significance of accounting for such impacts. This is related to the fundamental role of transportation infrastructure in maintaining the mobility of humans, various kinds of goods and commodities, which is critical for the economic activities between different industries and regions. In addition, increased transportation costs due to travel time perturbations have relatively bigger indirect impacts compared to the increased transportation costs for travel distances perturbations. This can be explained by the gap between average wages and vehicle operation costs. Besides, the high redundancy of the urban road network in the studied region moderates the perturbations in travel distances under transportation disruption scenarios. A future case study could focus on this multiway relationship between increases in travel time, distance, network redundancy and economic loss.

Besides, it can be observed that the economic impacts of transportation disruptions spread across regions. Initial impacts such as buildings and contents damages, business interruption as well as transportation disruptions all resulted in economic impacts to other regions outside the directly affected areas. On the other hand, losses and gains emerge simultaneously. For example, transportation disruptions in the LA Metro Area can lead to positive impacts in other regions, particularly for the Rest of U.S. This can be explained by the effects of production shifts and substitutions in consumption. The Rest of California and the SF Metro Region are more likely to be struck by the simulated event given the proximity in geo-location as well as strong economic connections between these regions and the directly affected region.

This paper has several limitations that can be improved in the future. First of all, the indirect impacts of repair and rehabilitation, government aid, and insurance are not included in this research. Previous research has proved that hazards can lead to positive impacts (e.g. caused by increasing demands for building materials), especially for regions that are close to the directly affected ones [73] or regions where large amounts of excess capacity exist in the rebuilding process [16]. The positive impacts need to be taken into account, especially for disaster impacts assessments [74]. This can be achieved based on dynamic CGE models if abundant post-disaster data are collected. Besides, fixed transportation demand and multi-stage linear recovery are assumed when the high-resolution transportation demand model is applied to estimate the indirect economic impacts caused by transportation perturbations under the scenario earthquake in the case study section. In addition, further and deeper research should be conducted on passenger flow perturbations and their indirect economic impacts. Despite the advantages of the TERM model, the impacts of increased travel times on household economic activities under time constraints cannot be readily investigated with the model. Besides, future work needs to be conducted to build circular (data-driven) interactions between CGE models and transportation network models, as travel demand can be affected by a fluctuation in transportation costs, and transportation costs can change if travel demand fluctuates which will further affect the economy.

In addition, it needs to be pointed out that the richness of data can have significant impacts on the evaluated indirect economic impacts caused by transportation infrastructure disruptions and disasters based on this framework. In this paper, the economic effects caused by substitutions between road transportation and other modes are not studied due to the scarcity of data. Given that over 80% of the population goes to work by private vehicles, while 7% of people use public transportation [75], the indirect economic impacts caused by passenger flow perturbations generated in the case study can be trusted and taken as an indicator to show the potential indirect economic impacts caused by transportation disruptions. However, for those regions with more diverse commuting means such as Tokyo [75], substitutions between different transportation modes can have great impacts on estimation. In addition, the assumption of fixed transportation demand has been made in the case study. However, different household transportation activities vary under disruption scenarios. For example, leisure trips are more likely to be canceled than business trips. The authors only evaluated the indirect impacts based on the transportation cost changes, without considering the economic impacts of households with less available time due to transportation perturbations. This is due to the lack of research and data on post-disaster household behavior changes both in terms of travel behavior and consumption preferences. Apart from that, the granularity of data concerning building damage costs and business interruptions could affect the reliability of estimation results. Last but not the least, the effects of various types of resilience tactics that both the providers of transportation services and general businesses can implement to cope with the disruptions [20,56,58], such as mode shift, telecommuting, and production recapture [64], are not taken into consideration.

6. Conclusion

This paper introduces an integrated framework to investigate the comprehensive economic impacts of transportation disruptions. The framework integrates results from explicit transportation network models as well as other sources of data into one of the state-of-the-art CGE models, the TERM model. A wide range of indicators representing potential direct effects due to transportation infrastructure disruptions are taken into consideration, including buildings and content losses, business interruption as well as transportation flow perturbations. The indirect economic impacts due to both freight flow perturbation and passenger flow perturbations are estimated, through built linkages between transportation network models and CGE models. These linkages are set based on a thorough investigation of the possible transportation disruption effects and their economic impacts. In addition, data that is essential to conduct a comprehensive estimation of the indirect economic impacts caused by transportation disruption is identified. Potential double counting issues during the calculation (especially in the fusion of multi-source data) and solutions are discussed as they relate to the implementation of this framework. A simulated earthquake scenario is used to test the capability of this framework. It needs to be noted that, although the authors use earthquake-induced transportation disruption scenarios for the case study, this does not limit the scope of this research to earthquakes or any other kinds of events. It can be generalized to any scenario where the transportation system undergoes a disruption to provide decision support for owners and operators of infrastructure.

Given the essential role played by transportation systems in today's economic systems, their complex characteristics arising from their networked nature as well as the fragility of their components, the economic meanings of transportation system disruptions need to be researched. Case study results show that the indirect economic impacts of freight flow and passenger flow perturbations can be over 300 million U.S. dollars.

This paper lays a foundation for further integration of transportation system analyses with economic modeling to achieve a comprehensive estimation of the indirect economic impacts due to transportation infrastructure disruptions. Besides, the authors identify the critical data needs for achieving a comprehensive and accurate evaluation of the indirect economic impacts due to transportation disruptions, including transportation system performance during the recovery period, travel demand changes, and detailed information on the direct losses. Particularly, there is a lack of data concerning changes in households' behaviors and changes in households' consumption structure under disasters as well as long-term transportation disruption scenarios. Closer collaboration between different domains needs to be achieved for the development of a fully integrated framework with two-way relationships between economic models and transportation network models.

Declaration of competing interest

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

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