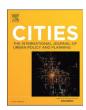


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Integrated infrastructure-plan analysis for resilience enhancement of post-hazards access to critical facilities

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ARTICLE INFO

Keywords: Access to critical facility Plan integration Resilience scorecard Integrated infrastructure-plan analysis

ABSTRACT

This paper presents an integrated infrastructure-policy framework to analyze policy attention on addressing road infrastructure network vulnerability in terms of accessing critical facilities in the aftermath of a flood. Coping with network vulnerability, particularly physical access to various critical facilities and the services they provide, is an essential step in achieving a resilient community. However, the extent to which the network of local plans addresses such vulnerability remains unclear. To bridge this gap, this paper uses the Plan Integration for Resilience Scorecard method to examine the infrastructure-related policy attention in relation to community vulnerability vis-a-vis disrupted access to critical facilities. The proposed framework is tested in a set of super neighborhoods in Houston, Texas. Findings reveal a discrepancy between the policy effort and network vulnerability and identifies strengths and weaknesses of various plans in addressing disrupted access to critical facilities. The framework introduced in this paper provides a tool for stakeholders to evaluate an existing network of plans and identify gaps for future resilience improvement.

1. Introduction

1.1. Background

Connected roads form the roadway network to provide essential transportation services for safe and efficient delivery of people and goods. People today have increasingly high expectations for transportation performance and low tolerance for disruption, which requires the transportation system to bounce quickly back from disruptions. This is closely tied to the concept of resilience. Resilience refers to the ability of a system's capacity to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (National Research Council, 2012;). Transportation resilience has multiple aspects, including (1) the ability to maintain its normal level of services or return to that level in a timely manner; (2) the ability to compensate for losses to allow functionality, even when that system is damaged or destroyed; (3) the ability to manage unexpected situations without complete failure; and (4) the ability to absorb consequence of disruption and maintain freight

mobility (Wan, Yang, Zhang, Yan, & Fan, 2018a; Weilant, Strong, & Miller, 2019).

Disruptions to the transportation network impacts community resilience by severely reducing economic productivity, harming local commercial activities and community well-being, and restricting people's mobility and accessibility (Weilant et al., 2019). Access to critical facilities (e.g., grocery store, pharmacy, hospital, shelter, gas station), in particular, is pivotal in maintaining community resilience, as people require access to critical resources and services to recover from the disruption, such as healthcare services (Dong, Wang, Mostafavi, & Gao, 2019, Dong, Esmalian, Farahmand, & Mostafavi, 2020). Moreover, risks associated with post-disaster access to critical facilities are not evenly distributed but concentrated in areas that are highly exposed to hazards (Song et al., 2019; Tsou, Hung, & Chang, 2005). One way to improve community resilience is to mitigate potential risks to ensure transportation network access to critical facilities during and after a natural hazard event (Forrest, Trell, & Woltjer, 2020).

A deep understanding of the community resilience requires a holistic

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vulnerability assessment considering disrupted transportation access to critical facilities. Transportation network failure may lead to disruption of access to critical facilities in two different ways: (1) direct impact to the road elements in the neighborhood due to road failure, such as a bridge collapse, road inundation, or road closure/work zone; (2) indirect impact due to isolating effect. For example, failure of roads in other region can cut off the paths between investigating neighborhood and the critical facilities. Although the disruption of access to critical facilities may result from both direct and indirect impacts, the corresponding impacts and risk mitigation approaches are different. The first disruption cause can be addressed by directly improving the physical infrastructure to mitigate the impact from the hazards, while the second disruption scenario requires a systematic understanding of the communities' risk profile. To do so, a network approach is needed to examine the vulnerability of different neighborhoods in terms of their accessibility to critical facilities in facing flood disruption. Dong, Yu, Farahmand, and Mostafavi (2019) proposed the robust component to evaluate network access to critical facilities in facing collective link failures, considering all possible paths. Given the disruption scenarios, vulnerability of different components of a network can be examined through a percolation network analysis approach (Dong, Mostafizi, Wang, Gao, & Li, 2020). Considering a network formed by links and nodes, percolation method refers to the process of removing a fraction of nodes and their connected links and then re-assessing the network functionality. This method enables a closer look at transportation vulnerability in terms of post-disaster access to critical facilities through a resilience lens.

A network of infrastructures also relies on a network of plans to guide infrastructure development and address infrastructure vulnerability to ensure its healthy functioning in both normal conditions and when facing disaster disruptions. Here, a network of plans refers to a collection of local and regional plans that address or affect local vulnerability to hazards. As we cannot prevent weather-related hazards, investing resources into infrastructure development and planning is critical in enhancing resilience (Weilant et al., 2019). Prioritizing planning can improve community resilience by including policies that anticipate adaptation, recovery, and vulnerability reduction before and after a disruption (Berke, Malecha, Yu, Lee, & Masterson, 2019; Godschalk, 2003; Lu & Stead, 2013). To improve the resilience of a transportation system, relevant agencies develop plans to guide investments such as retrofitting or rebuilding vulnerable assets in hazard zones to ensure the region's roadways are resilient to disruption (Hopkins & Knaap, 2018). However, plans are often developed independently, with each addressing a specific issue(s) in the region (Kaza & Hopkins, 2012). Moreover, these plans can be fragmented and poorly integrated, and may even potentially increase community vulnerability to hazards (Berke et al., 2015). For example, a hazard mitigation plan includes a policy that specifies avoidance of infrastructure investments in a floodplain (Li, Dong, & Mostafavi, 2019), but an infrastructure plan (road, or water/ sewer) proposes expansion of capacity that stimulates development in the same location. Failure to effectively integrate hazard mitigation and awareness throughout the network of local plans has become an international policy (United Nations Office for Disaster Risk Reduction., 2017) and national policy concern (FEMA, 2015).

To address this issue, Berke et al. (2015) developed a resilience scorecard to evaluate the degree of coordination among local plans and their combined effect on vulnerability to flooding, considering both positive and adverse impacts of the plans. A Plan Integration for Resilience Scorecard (PIRS) analysis can provide insights on conflicts between plan polices and can help local planners and emergency managers identify opportunities to align plans to reduce vulnerability in hazard-prone areas (Malecha, Masterson, Yu, & Berke, 2019). Although many plans have the overall goal of increasing community resilience, the focus of individual plans and their constituent policies may vary, such as retrofitting physical infrastructure or increasing green space (Afriyanie et al., 2020). Additionally, not all local plans will increase the resilience

of the transportation system.

There is a notable lack of understanding of the impacts of integrated resilience policy on enhancing network accessibility to critical facilities. To bridge this gap, an integrated infrastructure-plan analysis framework will be conducted to evaluate the extent to which local plans are integrated to improve post-disaster access to critical facilities—including grocery stores, pharmacies, and gas stations—using Hurricane Harvey's impact in Houston, Texas, as a scenario. Hurricane Harvey, a Category 4 hurricane that ravaged coastal Texas and the Houston region in late August 2017, caused \$190 billion in damage and revealed the community's vulnerability in terms of the transportation network and policy deficiencies in addressing such vulnerability (Winfree, 2019). This research aims to examine the degree to which local plans are integrated in terms of increasing transportation network resilience by enhancing accessibility to critical facilities.

1.2. Motivation and contribution

This study is largely motivated by the fact that plan and policy making often focus on enhancing regional disaster resilience without sufficient consideration of communities' needs for and access to critical services, especially in the aftermath of a disaster (Mitsova, Sapat, Esnard, & Lamadrid, 2020). Understanding remains limited regarding the influence of policy on community vulnerability to post-disaster transportation network access to critical facilities, such as grocery stores, pharmacies, and gas stations (Lang, Chen, Chan, Yung, & Lee, 2019). Houston, Texas, the fourth-most populated city in the U.S., located in Harris county, is the only major city without zoning regulations in North America, and is well known for its modest land use controls. Compared with other cities, governmentinitiated urban development policies for land use regulations are limited in Houston, which is comprised of 88 "super neighborhoods" (City of Houston, 2020). A super neighborhood is an area that is designated geographically, in which different entities such as residents, civic organizations, government, and different businesses cooperate and collaborate to identify and prioritize community needs, and plan for addressing them. Local planning typically focuses on economic growth, potentially conflicting with efforts to enhance hazard mitigation and resilient infrastructure. Using the case of a set of super neighborhoods in western Houston (Fig. 2) during a flooding scenario, this study will examine whether local infrastructure-related plans and policies address community needs for access to critical facilities after flood inundation. This research will contribute to the evolving discourse on resilience enhancement by introducing an integrated framework on strategic infrastructure plan development for community vulnerability to access disruption analysis, enabling stakeholders to examine the existing resilience plans and practices and identify gaps for resilience improvement in future plans.

The remainder of the paper is organized as follows. Section 2 reviews recent research on post-disaster road network connectivity and access to critical facilities, and on resilience of community networks of plans. Section 3 shows the methodology of the adopted robust component and plan integration for resilience scorecard. Section 4 presents the experiment results from a road network analysis through a case study in Houston and Section 5 analyze the resilience scorecard evaluation results of the local plans in the study area. Section 6 integrates the analysis results and discusses the discrepancy between the infrastructure vulnerability and planning endeavor on resilience enhancement. Finally, Section 7 presents a discussion on the results of this paper and Section 8 concludes the paper with major findings and limitations to address in future work.

2. Literature review

Community resilience can be defined as the ability of different organizations and other community social units to mitigate the risk of hazards, cope with the impact of disasters that occur, and manage restoration and recovery efforts to minimize the adverse consequences of disasters that cause social disruption (Bruneau et al., 2003). Infrastructures, as the backbones of community, support economic growth and prosperity by providing essential services (Ouyang, 2014). During an extreme event, the services provided by the infrastructure may be disrupted. As a consequence, users may be impacted by the disruption if the service afterwards does not meet their demands (Didier, Broccardo, Esposito, & Stojadinovic, 2018; Mitsova, Escaleras, Sapat, Esnard, & Lamadrid, 2019). Properly coping with such disruptions requires plans and policies that anticipate extreme events, reduce potential damages, and to enable rapid restoration of critical services and recovery (Berke, Song, & Stevens, 2009).

Achievement of community resilience entails three steps. The first is to understand the response of infrastructures to disaster, the extent of functionality loss, and vulnerability given different hazard scenarios (W. Huang & Ling, 2018; Ouyang, 2017). This is often referred to as resilience modeling and analysis and has been widely investigated in the current body of knowledge (Erath, Birdsall, Axhausen, & Hajdin, 2009; D. Li, Zhang, Zio, Havlin, & Kang, 2015; Miller & Baker, 2016). The second is to determine the public investment priorities and design standards that are needed for hazard mitigation and disaster response and recovery (Miles, Burton, & Kang, 2019; Zhang, Wang, & Nicholson, 2017). The third step is to apply information generated in the first two steps to devise and coordinate plan policies that aim to enhance community resilience. In this regard, the ability of a community to coordinate the plans that guide the location, design and capacity of infrastructure development is imperative to gain and maintain resilience (Berke et al., 2015; Malecha, Brand, & Berke, 2018). Integrating the three steps discussed above is critical for enhancing community resilience. It can reveal the extent to which policies in the plans that influence hazard mitigation and disaster recovery also address the needs and priorities that are reflected in the resilience analysis of infrastructures. This can help decision-makers identify gaps in community resilience planning and bridge them by incorporating policies into plans that target the infrastructure vulnerabilities, as well as helping them detect and remove conflicts between policies in the network of plans.

Road network is the focus of this study. The American Association of State Highway and Transportation Officials (AASHTO) standing committee on research generally defines road network resilience as "the ability of the system to recover and regain functionality after a major disruption or disaster" (U.S. Department of Transportation, 2014). Various tools and methods are developed for quantifying the resilience in transportation networks (Sun, Bocchini, & Davison, 2020; Wan, Yang, Zhang, Yan, & Fan, 2018). These transportation resilience assessment methods can be categorized into two groups: topological functionality metrics that focus on connectivity and centrality measures (Cheng, Lee, Lim, & Zhu, 2015; Zhang, Çetinkaya, & Sterbenz, 2013) and traffic related metrics that focus on travel time, throughput and congestion (Fotouhi, Moryadee, & Miller-Hooks, 2017; Hamad & Kikuchi, 2002). Different multi-dimensional methods have also been developed to provide more comprehensive look of transportation resilience (Khaghani & Jazizadeh, 2020). Besides, concepts such as adaptive and restorative capacities have been used by researchers in order to determine the resilience in transportation networks (Vugrin, Warren, & Ehlen, 2011). Moreover, infrastructure functional interdependency has also been included in transportation network resilience measurement (Dong et al., 2020; Kong, Simonovic, & Zhang, 2019; Ouyang, 2017).

2.1. Physical community vulnerability assessment

Infrastructure vulnerability assessment is the first step for an integrated infrastructure-plan assessment for resilience enhancement. Various studies attempt to formulate, quantify, and assess different aspects of road network resilience such as connectivity vulnerability, restoration capacity. In this research, an essential component of transportation resilience can be understood in terms of the network vulnerability considering the loss of access to critical facilities. Vulnerability

incorporates both weaknesses and consequences of failures in the network (Taylor, Sekhar, & D'Este, 2006). Various approaches have been adopted to assess road network vulnerability (Coles, Yu, Wilby, Green, & Herring, 2017; Jenelius & Mattsson, 2015; Maltinti, Melis, & Annunziata, 2012). One common approach for measuring road network vulnerability is quantification of accessibility level in the network (Berdica, 2002). Road network accessibility can be represented using different measures such as connectivity loss, travel delay, and network flow capacity drop (Chang, Peng, Ouyang, Elnashai, & Spencer, 2012; Dong, Yu, et al., 2019; Sullivan, Novak, Aultman-Hall, & Scott, 2010).

Accessibility analysis of road networks generally uses the propagation of network failure to determine the disruption on the network. The accessibility modeling approaches can be classified into two groups: mobility-based approaches and topology-based approaches. Mobilitybased approaches employ traffic data, such as daily travel demand to model accessibility (Jenelius, 2009; Jenelius & Mattsson, 2015; Tahmasbi & Haghshenas, 2019). However, such data is often not reliable for analysis in a disaster context, where the behavior of the system is considerably different from normal conditions. On the other hand, there are topologybased approaches that measure accessibility by simulating the failure propation on the network (Wang, Yang, Stanley, & Gao, 2019). There are many different methods for network failure modeling, such as percolation analysis (Bashan, Berezin, Buldyrev, & Havlin, 2013; Dong, Mostafizi, et al., 2020; Huang, Gao, Buldyrev, Havlin, & Stanley, 2011; Shao, Huang, Stanley, & Havlin, 2015), hybrid hydrological and agent-based modeing of tsunami inundation (Mostafizi, Dong, & Wang, 2017), and Bayesian network modeling of channel over-flow (Dong, Yu, et al., 2019). However, accessibility studies using statistical and spatial analysis techniques have limited capacity capturing the indirect impacts that can lead to disruption of access to critical facilities (Kocatepe et al., 2019; Ulak, Kocatepe, Ozguven, Horner, & Spainhour, 2017; Widener, Farber, Neutens, & Horner, 2015), percolation analysis enables a holistic look at postdisaster network access to critical facilities using a resilience lens.

Considering a network formed by links and nodes, percolation analysis refers to the process of removing a fraction of nodes and their connected links and re-assessing the network functionality (Shao et al., 2015). Percolation analysis has been widely applied to assess the connectivity and cascading failure analysis in infrastructure networks and interdependent infrastructure networks (Korkali, Veneman, Tivnan, Bagrow, & Hines, 2017; Ruj & Pal, 2014; Wang et al., 2019; Galvan & Agarwal, 2020). For example, Xiao and Yeh (2011) studied cascading link failures in power networks using a percolation approach. Percolation analysis has also been applied to investigate reliability of larg-scale communiation systems to better understand the network critical properties (Anjum, Wang, & Fang, 2019). Different types of percolation transitions in multilayer interdependent networks have shown to have association to network failure pattern (Cao, Liu, Jia, & Wang, 2021; Liu, Eisenberg, Seager, & Lai, 2018). There are also various studies investigating percolation behavior in transportation networks. For instance, percolation analysis has been applied to study the road network failure patterns in urban road networks during local inundations caused during flood events (Wang et al., 2019). Road network robustness has been examined using percolation-based indexes in different disruption strategies to understand the influence of network structure and failure pattern on network robustness (Casali & Heinimann, 2020). Integrated with multi-agent simulation analysis, percolation analysis has been applied to study the mobility impact of connected vehicles on the urban mobility (Mostafizi, Wang, Cox, Cramer, & Dong, 2017).

After mapping failures to the network, different performance metrics can be employed to measure changes in network connectivity during a disaster event. The largest connected component, known as the giant component, is often adopted as the accessibility measure (Dong, Mostafizi, et al., 2020). The giant component reflects the network vulnerability well when general accessibility is sought. However, it neglects the importance of the network's access to important nodes – also referred to as *critical facilities* in this paper – which make it impratical in a real life

post-disaster network vulnerability assessment. Dong, Mostafizi, et al. (2020) proposed the robust component to evaluate network access to critical facilities based on a collective link failure scenario. The robust component essentially calculates the ratio of network nodes/edges that have access to critical facilities considering the propagation of road failures due to flood inundation. We adopted the robust component metric in this paper to examine the network's access to critical facilities considering the components' all possible paths during flood disruptions. The percolation simulation enables integration of different critical facilities in various failure scenarios to investigate the network accessibility but requires a minimal amount of data. In this way, we can spatially map and visualize the network vulnerability in terms of the post-disaster access to critical facilities.

2.2. Planning for resilience and policy integration

Prioritizing planning and developing policies that anticipate adaptation, recovery, and vulnerability reduction before and after a disruption is critical for the enhancement of community resilience (Berke, Malecha, et al., 2019; Song et al., 2019; Sadiq and Noonan, 2015). Future land use and development patterns in a city or a neighborhood are guided by a network of plans (Berke et al., 2015; Berke, Malecha, et al, 2019). These plans are often developed by different agencies and groups and contain goals and policies to achieve their various interests (Laeni, van den Brink, & Arts, 2019), which may at times conflict (Hopkins & Knaap, 2018). Planning for hazard mitigation, especially, is often isolated from other planning processes, such as transportation planning and land use planning (Berke et al., 2015; Frazier, Walker, Kumari, & Thompson, 2013). Local plans often do not consider hazard mitigation implications, despite knowledge that having local plans that guide land use and development out of hazardous areas is critical in reducing future hazard vulnerability (Burby, 2006; Lyles, Berke, & Smith, 2016). The National Response Plan (NRP) also suggests planning to "... reduce the vulnerability to all natural and manmade hazards; and minimize the damage and assist in the recovery from any type of incident that occurs" (National Response Plan, 2004). Mitigation strategies should be mapped directly to areas of vulnerability—either areas that have already experienced disasters or areas identified through a vulnerability assessment (Asam, Bhat, Dix, Bauer, & Gopalakrishna, 2015). Community hazard mitigation plans are intended to identify vulnerability to hazards and propose actions to reduce the future impact of those hazards (Berke, Cooper, Salvesen, Spurlock, & Rausch, 2010; Godschalk, Beatley, Berke, Brower, & Kaiser, 1998; Horney et al., 2017). Hazard mitigation plans often lack a proper level of integration (Grafakos et al., 2020). If integrated with other plans, hazard mitigation plans can greatly enhance community resilience (Berke, Malecha, et al., 2019). Moreover, coordination among organizations and agencies involved in planning leads to a less fragmented policy scheme, which can contribute to community resilience enhancement (Li et al., 2019). Similarly, coordinated and well-prioritized planning contributes to the reduction of vulnerability in infrastructures, which lead to mitigation of consequences of a disaster (Farahmand et al., 2020).

The alarming rise in human and financial costs of natural hazards in recent decades prompted national (National Research Council, 2012) and international (United Nations General Assembly, 2015) calls for the development of guidance to help communities meet these challenges and adapt to changing conditions. Multiple "resilience scorecards" were produced in response, including the Resilient Communities Scorecard (Vermont Natural Resources Council, 2013), the Community Disaster Resilience Scorecard (Torrens Resilience Institute, 2015), and the Disaster Resilience Scorecard for Cities (United Nations Office for Disaster Risk Reduction, 2015). The Plan Integration for Resilience Scorecard (PIRS; also referred to hereafter as the "resilience scorecard") method (Berke et al., 2015, Berke, Yu et al., 2019, Berke, Malecha et al., 2019; Malecha et al., 2018; Yu, Brand, & Berke, 2020) was developed specifically to address the role of planning in this equation—in particular,

the problem of isolated hazard mitigation plans and policies, and the potential for conflict with other community plan guidance. The method is used to evaluate the extent of integration among a community network of plans so as to better coordinate hazard mitigation. The resilience scorecard helps researchers or community decision-makers "assess the degree of integration among plans that reduce vulnerability in different parts of a community, or in different planning districts" (Berke et al., 2015). In this method, vulnerability is defined as the susceptibility of people and the built environment to experience losses due to hazards that threaten the community (Berke, Malecha, et al., 2019). Using a resilience scorecard, valuable information can be produced to enhance community resilience by allowing planners and policymakers to better understand conflicts in plans, prioritize policies to target the most vulnerable areas, identify neighborhoods with high levels of social and physical vulnerability, and better inform decision making (Berke, Malecha, et al., 2019; Berke, Yu, Malecha, & Cooper, 2019). These capabilities make the resilience scorecard a useful tool for analyzing plan integration with respect to urban infrastructure systems. In fact, the resilience scorecard can help evaluate the extent to which plans and policies addressing infrastructure vulnerability. However, there is a gap in knowledge regarding the specific attention to infrastructure vulnerability in the evaluation of a network of plans. In this study, we propose an integrated framework for the assessment of infrastructure-plan analysis for resilience enhancement, with a focus on the vulnerability of a loss of access to critical facilities during flood events. The details of the proposed framework are elaborated in the next section.

3. Methodology

The integrated infrastructure-plan network analysis framework contains two components (as shown in Fig. 1): (1) physical vulnerability analysis that examines the roadway network's access to critical facilities (e.g., grocery, pharmacy, gas) in different flooding scenarios, and (2) plan policy analysis that quantifies policies to build resilience across the study area. The physical vulnerability analysis mainly focuses on examining each roadway intersection's connectivity to critical facilities in a flood event. To do this, we conduct a percolation analysis on the study super neighborhoods and measure the robust component size to represent the different district's post-disaster accessibility to critical facilities when facing direct and indirect network failures. Next, we perform the plan policy analysis, which is based on the "policy score" for each "district-hazard zone" (More details are explained in Section 3.2). Plan integration analysis is essentially quantifying the extent to which plans and policies are able to, both positively or negatively, affect accessibility to critical facilities. These two analyses combined together enable an integrated infrastructure-plan assessment framework. This integration is able to help identify critical areas where plans and policies fail to mitigate the infrastructure network vulnerability, whose failure would then lead to disruption of access to critical facilities. Three separate flood scenarios are investigated: a 100-year flood event and a 500-year flood event (1% and 0.2% annual chance of flooding, respectively), as well as a flood event like that which occurred during Hurricane Harvey.

The selected study area is comprised of a set of super neighborhoods in the western section of the City of Houston in Harris County, Texas—namely: Memorial, Eldridge/West Oaks, Briar Forest, and Westchase. A super neighborhood is a "geographically designated area where residents, civic organizations, institutions and businesses work together to identify, plan, and set priorities to address the needs and concerns of their community." (City of Houston, 2020). Fig. 2 shows the study area and the location of critical facilities (grocery stores) in the vicinity in Harris County.

Houston is one of the most flood-prone cities in the United States and has experienced multiple flood disasters in recent years (City of Houston, 2018; Federal Emergency Management Agency, 2019). Over 90 extreme weather events occurred in the U.S. from 2010 and 2017, and

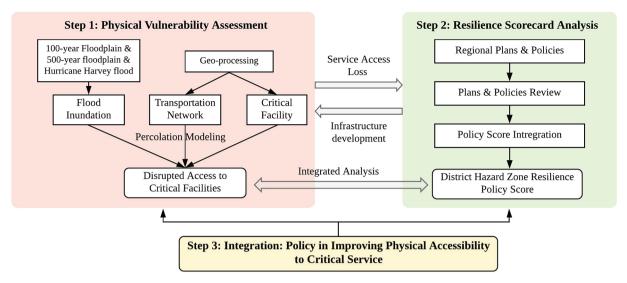


Fig. 1. Integrated infrastructure-plan network analysis framework.

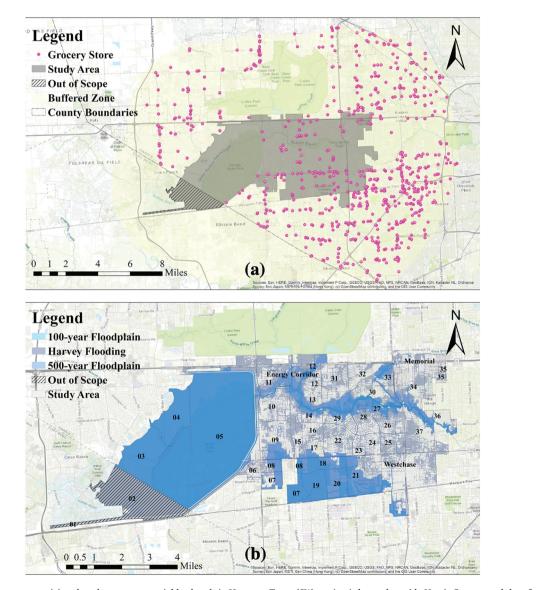


Fig. 2. Location of grocery stores (a) and study area super neighborhoods in Houston, Texas (SW portion is located outside Harris County, and therefore not included in this study).

43 of them struck Texas directly (Winfree, 2019). The most extreme of all was the unprecedented rainfall during Hurricane Harvey, beginning on August 25, 2017. During the following four days, more than one trillion gallons of water fell across Harris County, which flooded much of the city. This event required the release of water from the Addicks and Barker Reservoirs, located within the study area, leading to particularly destructive and cascading effects in the study super neighborhoods (Blake & Zelinsky, 2018), flooding a total area of 1800 miles² (4662 km²) and causing \$190 billion in damage (Winfree, 2019).

Extreme precipitation is, however, only one factor that makes Houston vulnerable to flooding. As in many cities – but perhaps more so in Houston – a combination of natural and built environment characteristics, as well as decisions made about land use and infrastructure, also contribute to the severity and effects of flooding (Brody, Highfield, & Kang, 2011; National Research Council, 2014). Thus, continued and creative investigation of these variables may provide insights that help reduce vulnerability.

3.1. Roadway network access score

A road network can be abstracted as a graph where nodes represent intersections and links represent roads. In this way, measuring the postdisaster performance of the disrupted road network can be equivalent to examining the network properties using graph theory-based methods. In an urban flooding scenario, the inundated roads can be treated as link removal during a network simulation. The amount of the removal or the likelihood of link removal varies based on the scale of the disruption and the probability that the hazards will occur. Consider a graph *G* of size *N*, a vertex *u* is considered to be connected to critical facility *k* if there is a path, regardless of distance, between u and k, which can be denoted as $\rho(u,k) = 1$. In the case of *K* critical facilities, the component that connects to a critical facility *k* can be denoted as $C_k = \{v_i | \rho(v_i, k) = 1, \forall i = 0, \}$ 1, ..., N}. A vertex is considered as robust during network disruption if it connects to at least one designated critical facility (Fig. 3). Therefore, the robust component of a network with disruption scale of ϕ can be defined as

$$\mathfrak{R}_{\phi} = igcup_{k=0,1,...,K} C_k$$

The computation of robust components can be achieved through Algorithm 1. Once the robust component rc is found for each disruption scenario, it can be mapped directly to the road network of the study area to identify vulnerable neighborhoods that have lost access to critical facilities. In this study, we examined the roadway network access to three types of critical facilities that are essential for post-disaster community recovery, namely; grocery stores, pharmacies, and gas stations.

Algorithm 1. Search robust component (rc).

Although we focus on a specific set of super neighborhoods in this study, people may still travel outside the region to access different resources, such as food, gas, and medicine. To include this potential in our study, we created a five-mile buffer (Liu, Han, & Cohen, 2015) and considered access to the critical facilities within the buffered area in the face of flood inundation disruption. Once each site's post-disaster access to critical facilities is determined through robust component analysis, their access indexes (0: no access; 1: has access) are aggregated based on the U.S. Census tract to which they belong, and the tracts' general access ratios are derived.

3.2. Network of Plans Resilience Score

The plan policy analysis component is achieved using the Plan Integration for Resilience Scorecard methodology (PIRS) (Berke et al., 2015; Malecha et al., 2019), which consists of two main steps. First, the study area is divided into mutually exclusive geographic units called "district-hazard zones", which correspond to the areas of a particular hazard (i.e., return-period storm event, such as a 500-year flood) within a U.S. Census tract. Census tracts are preferred because they provide a finer grain of analysis than the super neighborhood. Because we are focusing on three separate flood scenarios (100-year flood, 500-year flood, and Hurricane Harvey-type event), a census tract may contain up to three district-hazard zones. The combination of flood-scenario-based hazard zones and U.S. Census tracts yields 97 total district-hazard zones for the core study area (Fig. 2).

By dividing the study area into these smaller units, we are then able to "spatially evaluate" the existing network of plans (e.g., regional transportation plan, county hazard mitigation plan, city comprehensive plan, neighborhood-scale development plan) and understand how the plans and their constituent infrastructure-related policies affect different parts of the study area in different ways. Each document in the network of plans is content-analyzed to identify policies related to infrastructure that are likely to have either a positive or negative effect on floodresilience in some part of the study area. Examples of the scoring procedure for such policies are described in Table 1. Relevant policies are added to the resilience scorecard and then scores are assigned based on their effect on physical vulnerability. Using a + 1 (positive effect, or increase of resilience), -1 (negative effect, reduction of resilience), or 0 (neutral) scoring system, scores are assigned to all applicable policies across the entire network of plans and all district-hazard zones in the study area.

In the final scorecard, the sum total of scores for individual policies that affect a given district-hazard zone generates an aggregate "policy score", an index that can then be used to compare the effects of plans and their infrastructure policies on flood-resilience in different hazard zones and different parts of the study area. These policy scores are then integrated with the physical vulnerability analysis to better understand the relationships between policies and resilience, in terms of disrupted access to critical facilities.

```
K \Leftarrow \text{Critical facility list}
Network \Leftarrow \text{Super neighborhood road } (v_i, v_j)(i, j = 1, 2, ..., N)
Link_failure [\phi_m](m = 1: 100\text{-year flood, } 2: 500\text{-year flood, } 3: \text{Hurricane Harvey-type flood)}
m \Leftarrow 1
while m \le 3:
Disrupted_network = network.remove_edges(\phi_m)
for k in K do:
rc_m = \sum v_i, \forall v_i \mid \rho(v_i, k) = 1, i = 1, ..., N
end for
m += 1
end while
```

Fig. 3. Illustrative example of roadway robust component.

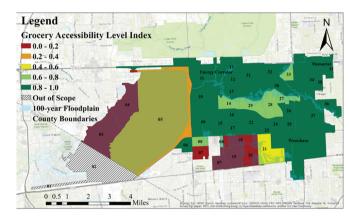
4. Disrupted access to critical facilities

Through calculating intersection's access to critical facilities and aggregating the access score (i.e., 0 for no access and 1 for having access) by the flood-hazard zones, we obtain each district's access to critical facilities in the face of flooding. We defined five ranges for accessibility level index (Low = 0.0-0.2, Low-Medium = 0.2-0.4, Medium = 0.4-0.6, Medium-High = 0.6-0.8, High = 0.8-1.0). Fig. 4 shows the mapped level of accessibility to grocery stores. The shadowed areas in each map show

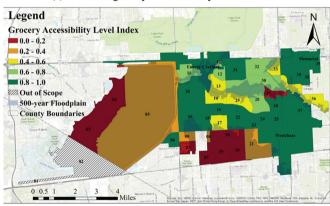
Table 1
Examples of plan policies, policy scores, and affected district-hazard zones.

Examples of plan policies, policy scores, and affected district-hazard zones.							
Plan policy	Policy score	Affected district-hazard zone(s)	Justification for policy score and placement				
MEMORIAL DR FROM BW 8 TO TALLOWOOD RD RECONSTRUCT ROADWAY INCLUDING DRAINAGE, ACCESS MANAGEMENT AND BICYCLE/PEDESTRIAN ACCOMMODATIONS (2017–2020 Transportation Improvement Plan, p. 3–68)	+1	Memorial District, Hurricane Harvey Extent hazard zone; Districts 34 and 36, 500-year floodplain and Hurricane Harvey Extent hazard zones	This action item in the regional TIP recommends infrastructure improvements that will reduce vulnerability by enhancing drainage. The roadway section slated for improvement crosses several districts and hazard zones in the northeast part of the study area.				
W BW 8 SHARED USE PATH FROM MEMORIAL DR TO BRIAR HILL CONSTRUCT SHARED USE PATH (2017–2020 Transportation Improvement Plan, p. 3–22)	0	Districts 27, 30, 36, and 37, 100-year and 500-year floodplain hazard zones	This policy, also in the TIP, proposes a shared use path to be constructed adjacent to BW 8 as it crosses Buffalo Bayou, potentially affecting several districts and hazard zones. However, the effects of this infrastructure improvement are neutral; even if the new pathway floods, it will have little effect on resilience in the area.				
New Local Streets Break Up Superblocks, Improve Community: New streets will create new connections and frontages that facilitate a mixeduse, denser environment. This network will contain many more options for pedestrian and automobile travel, development frontage and parking arrangements. (Westchase District Long-Range Plan, p. 27)	-1	Westchase District, 100- year floodplain and Hurricane Harvey Extent hazard zones	This policy recommendation aims to increase development intensity in a section of Westchase District located partly in the 100-year floodplain and Hurricane Harvey Extent hazard zones. This may increase vulnerability by placing more people and structures, and roadways in harm's way.				

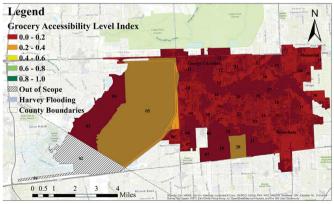
different floodplain extent. The 100-year floodplain (Fig. 4a) is the smallest and most likely flood scenario of those being studied; there is ostensibly a 1% annual chance of such a flood occurring. The 500-year floodplain (Fig. 4b) is larger and corresponds to the area that would



(a) Access to grocery store in 100-year flood scenario



(b) Access to grocery store in 500-year flood scenario



(c) Access to grocery store in Hurricane Harvey flood scenario

Fig. 4. Summary of access to critical facilities in facing different magnitudes of flood.

be flooded by an even larger event, which is less likely (0.2% annual chance). Finally, the Hurricane Harvey floodplain (Fig. 4c) is the largest, covering a majority of the study area, and corresponds to an extreme and relatively unlikely – though demonstrably possible – flood event.

Overall, as the flood exposure area increases from the 100-year to 500-year floodplain to Hurricane Harvey flood extent, the network's access to critical facilities decreases. We can observe from Fig. 4(a) that in the 100-year floodplain scenarios, districts 07, 18, 19, and 20 show high vulnerability (*low* accessibility level index) as they are nearly fully located in the floodplain. With the roads being inundated, residents will have few routes to reach critical facilities outside of the floodplain. Access is further limited by inundation of critical facilities in the floodplain. District 20 is particularly vulnerable with all paths to critical facilities cut. While the neighborhood will remain unflooded, district 20 is surrounded by floodplain creating an island effect. Since district 02 is outside of Harris County and districts 03, 04, and 05 are in the Barker reservoir and there are no residents in the area, we exclude them from the discussion. Districts 14, 21, 27, 28, 29, and 33 show moderate impacts from the 100-year flooding (*medium* accessibility level index).

Looking at the 500-year flooding scenario shown in Fig. 4 (b), districts 02, 03, 04, 07, 18, 19, 20, and 27 (low accessibility level index), and 05, 08 and 21 (low-medium accessibility level index), are highly vulnerable in terms of losing access to grocery stores as the majority of the land in these districts is located in the 500-year floodplain. Districts 13, 14, 17, 29, 33, and 36 (medium accessibility index) are partially covered by the floodplain, which will lead to the inundation of many intersections

Turning now to the Harvey flooding scenario shown in Fig. 4 (c), most of the districts have *low* accessibility level index for access to grocery stores. This is mainly due to the extensive flooding in the study area. Although not all the districts are covered by the flood (as show in Fig. 2), accessibility is still low because the flood control infrastructure was incapable of coping with overwhelming discharging demand and the runoff spread over the road network. This directly cut off access to grocery stores and also created islanding effects by isolating non-flooded neighborhoods from connecting to the grocery stores.

From the quantitative accessibility analysis shown in Fig. 4, we can conclude that the study location can cope with 500-year type flood events relatively well, except for certain districts which are predicted to be entirely covered by the flood. Additionally, certain areas suffer from the access loss due to the islanding effect where all the paths to the critical facilities are cut off but the neighborhoods remain unflooded. Infrastructure development and protection efforts, such as flood control infrastructure construction and retrofitting, infrastructure elevation, and green infrastructure development, should be targeted toward those highly vulnerable areas that are in danger of losing access to essential resources (e.g., food, medicine, and gas) to maintain their well-being in the immediate aftermath of a disaster. The study area is clearly not yet prepared for another catastrophic event like Hurricane Harvey, as most of the region will lose access to grocery stores. In this case, overall infrastructure resilience needs to be strategically enhanced through local and regional plans.

5. Infrastructure policy resilience score

After thoroughly reviewing the relevant network of plans, we derived scores that reflect the relative infrastructure policy-related resilience in the study area. Following the PIRS method (Section 3.2), 18 local-, city-, and regional-scale plans were evaluated with respect to their effects on infrastructure resilience. Shown in Table 2, these include plans used to guide transportation, hazard mitigation, and development. A resilience score (PIRS) analysis treats different flood zones as mutually exclusive, because the goal is to understand how plans and policies affect the different parts of the city, and especially the differences between designated flood hazard zones, such as the FEMA-delineated 100-year floodplain, and other areas that are less heavily regulated. For

Table 2Total policy resilience score by hazard zone.

Plan	100-year floodplain	500-year floodplain ^a	Hurricane Harvey ^b
Our Great Region 2040 + 'Strategy Playbook'	128 ^c	12	-4
Houston Stronger (2018)	112	97	87
Gulf-Houston Regional Conservation Plan (2017)	52	40	36
Harris County Flood Control District Federal Briefing (2017)	27	28	25
2040 Regional Transportation Plan [RTP] (Update 2016) + 2017–2020 Transportation Improvement Plan [TIP]	-14	-9	- 7
Hazard Mitigation Plan Update (Draft 2017)	119	92	94
Plan Houston (2015)	62	64	68
Houston Parks & Recreation Department Master Plan (2015)	0	0	0
The Energy Corridor District Unified Transportation Plan (2016–2020)	0	0	0
The Energy Corridor District 2015 Master Plan	-3	-5	-4
Energy Corridor Livable Centers Plan (2010)	0	0	-6
Energy Corridor District Bicycle Master Plan (2010)	0	0	0
Memorial Management District 2014–2024 Service & Improvement Plan & Assessment Plan	0	0	0
Westchase District Long-Range Plan (2006)	0	1	0
2009 Master Plan: Addicks and Barker Reservoirs	3	3	0
West Houston Plan 2050 + '2010 Update'	26	28	32
West Houston Trails Master Plan (2011)	0	0	0
West Houston Mobility Plan (2015)	-14	-10	-16

- ^a Excludes 100-year floodplain.
- ^b Excludes 100-year floodplain and 500-year floodplain.
- ^c Sum of policy scores across districts for each hazard zone.

example, a policy prohibiting development only in the 100-year flood-plain still permits it in areas just outside/upland of this zone—which may, in fact, be in the 500-year floodplain. Such a policy therefore increases resilience in the 100-year floodplain (+1 score), but not in the 500-year floodplain (score of 0). Policies that truly apply to the entire 500-year floodplain (which includes the 100-year floodplain) are scored and the same for both hazard zones (whether +1 or -1).

To compare the total resilience scores for each plan by the type of flood scenario (and zone), we summarized the scores in Table 2, where the score of each plan is the sum of policy scores across the districts for the specified hazard zone. Notably, the resilience scorecard reveals that Our Great Region 2040, Houston Stronger, Gulf-Houston Regional Conservation Plan, Hazard Mitigation Plan Update, Plan Houston, and West Houston Plan 2050 receive the highest scores in terms of enhancing infrastructure resilience for accessing grocery stores. Houston Stronger (2018) shows high scores across all hazard zones, reflecting its many and wide-ranging policies aimed at enhancing resilience through infrastructure policy investment following Hurricane Harvey, as a way to help the city to cope more effectively with future disasters. The Hazard Mitigation Plan Update scores similarly high across the board. This plan aims to decrease physical vulnerability in different district hazard zones through policies like development regulations, land acquisition, and relocation of critical facilities.

In contrast, the 2040 Regional Transportation Plan, 2017–2020 Transportation Improvement Plan, Energy Corridor District 2015 Master

Plan, and West Houston Mobility Plan show negative overall scores; a preponderance of their policies is likely to increase the physical vulnerability of neighborhoods in accessing critical facilities after flooding events. This is largely due to the focus of these transportation development and mobility plans on increasing road network infrastructure and connectivity in flood-prone areas. Adding infrastructure in the floodplain also stimulates development and increases physical vulnerability. Moreover, the development of transportation infrastructure sometimes neglects the development of nearby flood control infrastructure, largely due to insufficient coordination between the two sectors (Li et al., 2019; Li et al., 2020). Values may also differ with regard to flood protection strategy prioritizations (Farahmand et al., 2020; Pathak, Zhang, & Ganapati, 2020), which leads to insufficient discharge capacity for rainfall runoff and cascading floods on the road network.

Total policy scores in other plans are inconsistent across the different hazard zones. For example, Our Great Region 2040 presents a total resilience score of -4 in the Hurricane Harvey hazard zone, suggesting a lack of recognition of increasing flood hazards and little preparation for Hurricane Harvey-like events.

Fig. 5 displays policy scores by district-hazard zone across the study area. To better visualize the policy scores, we divided the scores into four ranges (Very low = 0, Low = 1-8, Medium = 9-16, High = 17-24). Although a resilience score of 24 is at a high level in this case, it might be a lower level when study region expands. However, we need to limit the analysis within the study region. Results show the effects of infrastructure-related policies on vulnerability in all three hazard zones, with concentrations of lower scores evident along the Buffalo Bayou (e. g., Districts 10, 11, 12, 13, 14, 26, 27, 28, 29, 30, 36, 37) and southern region (e.g., Districts 07, 18, 19, 20, and 21). Districts 03, 04, and 05 are located in the Barker reservoir, and thus receive considerable attention related to resilient infrastructure development (including preservation and enhancement of green infrastructure). Districts 08, 16, 20, 22, 23, 24, and 25 have Very low scores in 500-year floodplain zone (map b) and Hurricane Harvey Extent zone (map c). This indicates that policies

focused on infrastructure in these areas have a relatively narrow consideration of the impacts of flooding on infrastructure, without recognizing the increasing frequency and intensity of floods, leaving them unprepared and resulting in much greater losses when 500-year and Hurricane Harvey types of flood events hit the region. A similar pattern occurs in Energy Corridor and District 18, which have *high* policy scores in the 100-year floodplain zone and lower (*medium and low*) scores in the 500-year floodplain zone. Very few policies focus on the areas outside the 500-year floodplain, however, many of which flooded during Hurricane Harvey.

Of course, network resilience enhancement is not limited to physical infrastructure development. Green infrastructure improvements, such as creating open green space or building retention ponds, can also help improve the resilience of the study area and its networks (Bush & Doyon, 2019). For example, a retention pond can store rainfall and street runoff and prevents the spread of channel overflow on the streets, which further eliminates mobility and accessibility loss risks. Therefore, enhancing indirectly infrastructure-related policy is also a positive alternative in improving network resilience.

6. Integrated analysis of access vulnerability and policy score

Knowing the network vulnerability of each hazard zone in terms of losing access to critical facilities during flooding and the corresponding policy resilience scores, we can determine how the infrastructure policies addresses the physical vulnerability. In this integrated analysis, we will mainly focus on the zones that are vulnerable to losing access to critical facilities during floods, since resilient places do not require extensive policy attention in strengthening their network accessibility performance. When we zoom into Fig. 4 (a) we can see that the accessibility to critical facilities in district 07, 18, 19, 20, and 21 (mid-east of the study area) are severely impacted by the flooding due to the high concentration of facilities within the 100-year floodplain. Although most infrastructure development has been dedicated to the 100-year

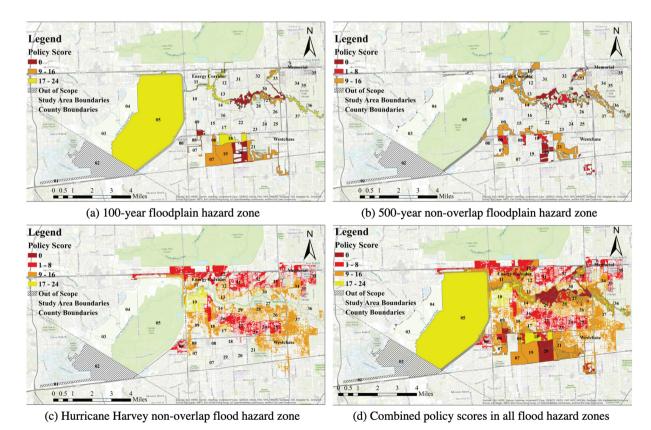


Fig. 5. Physical infrastructure-related policy scores in different flood scenarios.

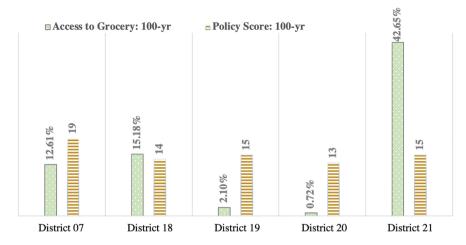


Fig. 6. Accessibility and policy scores for impacted 100-year floodplain zones.

floodplain zones along Buffalo Bayou, these communities receive little impact from the flooding as many critical facilities are located along the Bayou. Comparing the affected zones' network vulnerability in terms of access loss to critical facilities and corresponding policy scores in the 100-year zones, we can conclude that plan policy scores do not target districts that are the most vulnerable in access to critical facilities. Fig. 6 indicates that policy scores are generally consistent for the aforementioned five districts, but there is wide variability in access scores. Notably, the two districts with the lowest accessibility scores (19 and 20) receive about the same policy scores as district 21 with the highest accessibility score. This unveils the resilience gap in addressing the infrastructure network vulnerability of accessing critical facilities in the aftermath of the hazards disruption and necessitates the policy attention in these vulnerable districts.

The gap between plan policies to build resilience and reduce infrastructure vulnerability remains in the 500-year flood scenario. As the flood exposure severity increases to a 500-year flood, accessibility to grocery stores is impacted on a larger scale. Beyond districts 07, 18, 19, 20, and 21 (south of the study area), which are severely impacted, districts 08, 13, 14, 27, 29, 33, and 36 (mid-east and northeast of the study area) lose more than half of their access to grocery stores. Contrary to the consistent moderate policy scores in 100-year zones, policy score in 500-year zones varies across districts. Looking at the policy scores in these zones (shown in Fig. 7), we find some districts have *medium* policy scores (greater than 8) in the 500-year zones; this is true of districts 07, 13, 14, 17, 18, 21, 29, and 36. However, districts 08, 19, 20, 27, and 33 have *very low* or *low* policy scores, which suggests a lack of policy strength in decreasing the network vulnerability of disrupted access to

critical facilities. In particular, districts 19, 20, and 33 not only have *very low* or *low* policy scores in the 500-year zones, but also have *very low* or *low* scores in the 100-year zone as well. The consistently low scores in both the 100-year and 500-year zones suggest that these areas are not mitigating flood risks they are exposed to and related access to critical facilities.

When the flood escalates to Hurricane Harvey type of flooding, access to grocery stores will be nearly entirely disrupted. However, policy scores of the corresponding Harvey flood hazard zones in many districts show *very low* or *low* infrastructure-policy scores. Specifically, districts 06, 12, 16, 18, 19, 20 (south of the study area), 23, 24, 25 (mid-east of the study area), 31, 32, 33, 35, Energy Corridor, and Memorial (north of the study area) have *very low* or *low* policy score (8 or less) (shown in Fig. 8). The mismatch between extreme physical access vulnerability and low resilience policy score indicates that regional plans on infrastructure development are not enhancing resilience and access to critical facilities in these areas. Additionally, the low policy score districts are all located outside of the floodplains, which indicates a lack of recognition of the increasing intensity of natural hazards.

7. Discussion

These comparisons between district accessibility to critical facilities and policy scores highlight the discrepancy between physical vulnerability in terms of access loss to critical facilities and policy efforts to enhance resilience. This mismatch reveals a disconcerting absence of consideration of the need to maintain and improve access to critical facilities for all parts of the community. Planning, policy, and

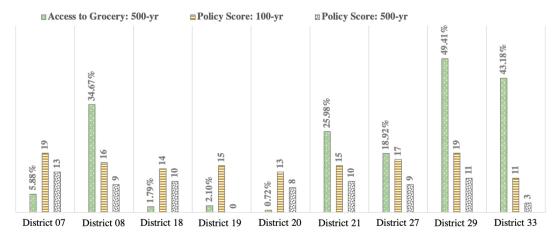


Fig. 7. Accessibility and policy scores for impacted 500-year floodplain zones.

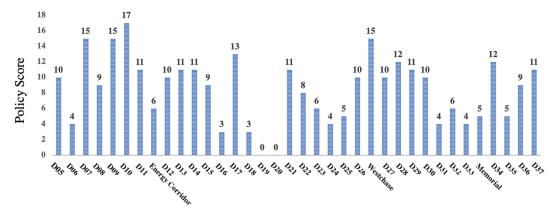


Fig. 8. Policy scores for Harvey non-overlap zones.

engineering decisions related to infrastructure may mean the difference between the relative suffering and well-being of residents in the aftermath a flood event. The approach must therefore be holistic, and especially mindful of the importance of maintaining accessibility to critical facilities. Future planning and programming should place the greatest focus on the most at-risk areas—a process facilitated by empirical findings like those from the integrated infrastructure-plan analysis presented in this article.

The findings also imply a lack of institutional connectedness among plans and actors, which reinforces the need for an integrated infrastructure-plan analysis framework to facilitate better coordination among actors and consideration of infrastructure vulnerability and interdependence across multiple (Dong, Wang, Mostafizi, & Song, 2020). Mounting evidence from studies like this, focused on the complex relationships involved in safeguarding communities like Houston from increasingly frequent flooding (Dong, Wang, et al., 2020; Farahmand et al., 2020; Malecha, Woodruff, & Berke, 2021), suggest the need to reevaluate how decisions are made about how and where to build.

The resilience scorecard is useful for identifying how plans may increase vulnerability to flooding, however, plans often balance multiple competing priorities. For example, policies that increase density in risky locations (example 3 in Table 1) may increase physical vulnerability to flooding but provide other benefits such as reduced air pollution, greater walkability and livability, and economic development. The derived resilience score aims to provide a plan integration evaluation from the resilience perspective.

8. Conclusion

Communities' physical and social vulnerability have been researched in various studies (Berke, Malecha, et al., 2019; Dong, Esmalian, et al., 2020; Zeng, Lan, Hamidi, & Zou, 2020). In particular, post-disaster physical network access to critical facilities is essential in maintaining a community's well-being and requires targeted physical infrastructure development for network resilience enhancement. Despite multiple studies and applications (Berke, Malecha, et al., 2019; Malecha et al., 2018; Yu et al., 2020), the Plan Integration for Resilience Scorecard has not yet been used to directly examine the physical-infrastructure-related policy scores to improve network resilience and address disrupted access to critical facilities. To bridge this gap, we examined the integration of both network vulnerability in accessing critical facilities and the infrastructure-related policy scores.

This paper enables a framework to integrate infrastructure network vulnerability considering access loss in facing flooding with infrastructure policy for examining existing regional plans. It provides the planners, stakeholders, and decision-makers an analysis tool for identifying opportunities to better plan for and target network access improvements in future plans, as well as informing hazard mitigation and disaster relief

efforts for future hazards. The proposed framework is tested on a group of super neighborhoods in Houston in three different flooding scenarios (e.g., 100-year floodplain, 500-year floodplain, and Hurricane Harvey flood) with grocery stores. The comparison between network vulnerability to grocery store accessibility and policy scores reveals that many districts lack policy attention to resilience outside of floodplains—as the scale of flooding increases, policy scores often decrease. In particular, many districts were exposed to severe risk of losing access to grocery stores in the Hurricane Harvey flood scenario, but policy scores corresponding to these hazard zones have low scores in terms of strengthening their infrastructure resilience. The discrepancy shows a lack of recognition of increasing intensity of the natural hazards, which leaves the community unprepared for the next mega-flood event. The analysis result highlights the need for greater attention to infrastructure resilience improvements in future plan development.

Our initial application of the integrated infrastructure-policy analysis framework is limited, as we only investigated the network vulnerability in accessing three types of critical facilities and looked at a relatively small spatial extent. More critical services and infrastructures are essential for the communities to maintain their well-being in the aftermath of a disaster. But the accessibility evaluation methodology, resilience scorecard, and integrated infrastructure-plan analysis framework can be employed in various cases and the physical indicators could be supplemented with additional scenarios (e.g., school, emergency shelter, jobs, etc.) to determine the vulnerability of communities to hazards. Besides, different communities have different needs for critical services, and socially vulnerable communities have a lower level of capacity to cope with the service disruption (Esmalian, Dong, & Mostafavi, 2021). For example, high-income households may have more resources for better disaster preparedness (e.g., generator, stock for food, water, and medicine), while their disadvantaged neighborhoods have fewer resources but dire needs for critical services. Therefore, transportation network vulnerability considering access loss to critical facilities alone cannot fully explain the community vulnerability. Future research will integrate the social vulnerability concept into the proposed infrastructure-plan framework to addressing the rising health inequities challenges in coastal communities. Moreover, different types of critical facilities with different functional mechanisms. Access disruption may not be the only source of infrastructure failure. Future studies will include multi-dimensional failure characterization to improve the physical infrastructure network vulnerability assessment.

CRediT authorship contribution statement

Shangjia Dong: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Matthew Malecha:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing –

review & editing, Visualization. **Hamed Farahmand:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Ali Mostafavi:** Conceptualization, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Philip R. Berke:** Conceptualization, Formal analysis, Writing – review & editing. **Sierra C. Woodruff:** Conceptualization, Formal analysis, Writing – review & editing.

Declaration of competing interest

None.

Acknowledgement

The authors would like to acknowledge funding support from the National Science Foundation CRISP 2.0 Type 2 #1832662: "Anatomy of Coupled Human-Infrastructure Systems Resilience to Urban Flooding: Integrated Assessment of Social, Institutional, and Physical Networks". The authors would also like to thank Mr. Connor Lutz for the critical facility data collection. Any opinions, findings, and conclusion or recommendations expressed in this research are those of the authors and do not necessarily reflect the view of the funding agencies.

References

- Afriyanie, D., Julian, M. M., Riqqi, A., Akbar, R., Suroso, D. S. A., & Kustiwan, I. (2020). Re-framing urban green spaces planning for flood protection through socio-ecological resilience in Bandung City, Indonesia. *Cities*, 101, Article 102710. https://doi.org/10.1016/j.cities.2020.102710.
- Anjum, M. D. N., Wang, H., & Fang, H. (2019). Percolation analysis of large-scale wireless balloon networks. *Digital Communications and Networks, Changing University* of Posts and Telecommunications, 5(2), 84–93.
- Asam, S., Bhat, C., Dix, B., Bauer, J., & Gopalakrishna, D. (2015). Technical report: Climate change adaptation guide for transportation systems management, operations, and maintenance. United States Department of Transportation, Federal Highway Administration.
- Bashan, A., Berezin, Y., Buldyrev, S. V., & Havlin, S. (2013). The extreme vulnerability of interdependent spatially embedded networks. *Nature Physics*, 9(10), 667–672. https://doi.org/10.1038/nphys2727.
- Berdica, K. (2002). An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy*, 9(2), 117–127. https://doi.org/10.1016/ S0967-070X(02)00011-2.
- Berke, P., Cooper, J., Salvesen, D., Spurlock, D., & Rausch, C. (2010). Disaster plans: Challenges and choices to build the resiliency of vulnerable populations. In International Journal of Mass Emergencies and Disasters, 28.
- Berke, P., Newman, G., Lee, J., Combs, T., Kolosna, C., & Salvesen, D. (2015). Evaluation of networks of plans and vulnerability to hazards and climate change: A resilience scorecard. *Journal of the American Planning Association*, 81(4), 287–302. https://doi. org/10.1080/01944363.2015.1093954.
- Berke, P., Yu, S., Malecha, M., & Cooper, J. (2019). Plans that disrupt development: Equity policies and social vulnerability in six coastal cities. *Journal of Planning Education and Research*., Article 0739456X1986114. https://doi.org/10.1177/0739456X19861144.
- Berke, P. R., Malecha, M. L., Yu, S., Lee, J., & Masterson, J. H. (2019). Plan integration for resilience scorecard: Evaluating networks of plans in six US coastal cities. *Journal* of Environmental Planning and Management, 62(5), 901–920. https://doi.org/ 10.1080/09640568.2018.1453354.
- Berke, P. R., Song, Y., & Stevens, M. (2009). Integrating hazard mitigation into New Urban and conventional developments. *Journal of Planning Education and Research*, 28(4), 441–455. https://doi.org/10.1177/0739456X09331550.
- Blake, E. S., & Zelinsky, D. A. (2018). National Hurricane Center tropical cyclone report. Hurricane Harvey. Retrieved from https://www.nhc.noaa.gov/data/tcr/ AL092017 Harvey.pdf.
- Brody, S. D., Highfield, W. E., & Kang, J. E. (2011). Rising waters: The causes and consequences of flooding in the United States. Cambridge, UK: Cambridge University Proces
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., ... von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733–752. https://doi.org/10.1193/1.1623497.
- Burby, R. J. (2006). Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *Annals of the American Academy of Political and Social Science*, 604(1), 171–191. https://doi.org/10.1177/0002716205284676.
- Bush, J., & Doyon, A. (2019). Building urban resilience with nature-based solutions: How can urban planning contribute? Cities, 95, Article 102483. https://doi.org/10.1016/ j.cities.2019.102483.

Cao, Y. Y., Liu, R. R., Jia, C. X., & Wang, B. H. (2021). Percolation in multilayer complex networks with connectivity and interdependency topological structures. In , vol. 92. Communications in nonlinear science and numerical simulation (p. 105492). Elsevier B.

- Casali, Y., & Heinimann, H. R. (2020). Robustness response of the Zurich road network under different disruption processes. In , vol. 81. Computers, environment and urban systems (p. 101460). Elsevier Ltd.
- Chang, L., Peng, F., Ouyang, Y., Elnashai, A. S., & Spencer, B. F. (2012). Bridge seismic retrofit program planning to maximize postearthquake transportation network capacity. *Journal of Infrastructure Systems*, 18(2), 75–88. https://doi.org/10.1061/ (ASCE)IS.1943-555X.0000082.
- Cheng, Y.-Y., Lee, R. K.-W., Lim, E.-P., & Zhu, F. (2015). Measuring centralities for transportation networks beyond structures (pp. 23–39). Cham: Springer.
- Chengpeng, W., Yang, Z., Zhang, D., Yan, X., & Fan, S. (2018). Resilience in transportation systems: A systematic review and future directions. *Transport Reviews*, 38(4), 479–498. https://doi.org/10.1080/01441647.2017.1383532.
- City of Houston. (2018). Hazard mitigation plan update 2018. Houston, TX. Retrieved from https://s3-us-west-2.amazonaws.com/uasi-jtti/wp-content/uploads/sites/29/2 018/05/16202024/City-of-Houston-HMAP-Update-3.13.18-3.12.23-PUBLIC-C OPY_compressed.pdf.
- Coles, D., Yu, D., Wilby, R. L., Green, D., & Herring, Z. (2017). Beyond "flood hotspots": Modelling emergency service accessibility during flooding in York, UK. *Journal of Hydrology*, 546, 419–436. https://doi.org/10.1016/j.jhydrol.2016.12.013.
- Didier, M., Broccardo, M., Esposito, S., & Stojadinovic, B. (2018). A compositional demand/supply framework to quantify the resilience of civil infrastructure systems (Re-CoDeS). Sustainable and Resilient Infrastructure, 3(2), 86–102. https://doi.org/ 10.1080/23789689.2017.1364560.
- Dong, S., Esmalian, A., Farahmand, H., & Mostafavi, A. (2020). An integrated physical-social analysis of disrupted access to critical facilities and community service-loss tolerance in urban flooding. *Computers, Environment and Urban Systems*, 80, Article 101443. https://doi.org/10.1016/j.compenvurbsys.2019.101443.
- Dong, S., Li, Q., Farahmand, H., Mostafavi, A., Berke, P., & Vedlitz, A. (2020). Institutional connectedness in resilience planning and management of interdependent infrastructure systems. *Journal of Management in Engineering*. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000839.
- Dong, S., Mostafizi, A., Wang, H., Gao, J., & Li, X. (2020). Measuring the topological robustness of transportation networks to disaster-induced failures: A percolation approach. *Journal of Infrastructure Systems*, 26(2), Article 04020009. https://doi.org/ 10.1061/(ASCE)IS.1943-555X.0000533.
- Dong, S., Wang, H., Mostafavi, A., & Gao, J. (2019). Robust component: A robustness measure that incorporates access to critical facilities under disruptions. *Journal of the Royal Society Interface*, 16(157), Article 20190149. https://doi.org/10.1098/ rsif.2019.0149.
- Dong, S., Wang, H., Mostafizi, A., & Song, X. (2020). A network-of-networks percolation analysis of cascading failures in spatially co-located road-sewer infrastructure networks. *Physica A: Statistical Mechanics and its Applications*, 538, Article 122971. https://doi.org/10.1016/j.physa.2019.122971.
- Dong, S., Yu, T., Farahmand, H., & Mostafavi, A. (2019). Bayesian modeling of flood control networks for failure cascade characterization and vulnerability assessment. Computer-Aided Civil and Infrastructure Engineering. https://doi.org/10.1111/ mice.12527.
- Erath, A., Birdsall, J., Axhausen, K. W., & Hajdin, R. (2009). Vulnerability assessment methodology for Swiss road network. Transportation Research Record: Journal of the Transportation Research Board, 2137(1), 118–126. https://doi.org/10.3141/2137-13.
- Esmalian, A., Dong, S., & Mostafavi, A. (2021). Susceptibility curves for humans: Empirical survival models for determining household-level disturbances from hazards-induced infrastructure service disruptions. Sustainable Cities and Society, 66, Article 102694. https://doi.org/10.1016/j.scs.2020.102694.
- Farahmand, H., Dong, S., Mostafavi, A., Berke, P. R., Woodruff, S. C., Hannibal, B., & Vedlitz, A. (2020). Institutional congruence for resilience management in interdependent infrastructure systems. *International Journal of Disaster Risk Reduction*, 46. https://doi.org/10.1016/j.ijdrr.2020.101515.
- Federal Emergency Management Agency [FEMA]. (2015). Plan integration: Linking local planning efforts. Retrieved from https://www.fema.gov/media-library-data/1440 522008134-db097cc285bf741986b48fdcef31c6e/R3_Plan_Integration_0812_508. pdf.
- Federal Emergency Management Agency [FEMA]. (2019). Data visualization: Disaster declarations for states and counties. Retrieved from https://www.fema.gov/data-visualization-disaster-declarations-states-and-counties.
- Forrest, S. A., Trell, E. M., & Woltjer, J. (2020). Socio-spatial inequalities in flood resilience: Rainfall flooding in the city of Arnhem. *Cities*, 105, Article 102843. https://doi.org/10.1016/j.cities.2020.102843.
- Fotouhi, H., Moryadee, S., & Miller-Hooks, E. (2017). Quantifying the resilience of an urban traffic-electric power coupled system. *Reliability Engineering and System Safety*, 163, 79–94. Elsevier Ltd,.
- Frazier, T. G., Walker, M. H., Kumari, A., & Thompson, C. M. (2013). Opportunities and constraints to hazard mitigation planning. Applied Geography, Pergamon, 40, 52–60.
- Galvan, G., & Agarwal, J. (2020). Assessing the vulnerability of infrastructure networks based on distribution measures. In , vol. 196. Reliability Engineering and System Safety (p. 106743). Elsevier Ltd.
- Godschalk, D. (2003). Urban hazard mitigation: Creating resilient cities. *Natural Hazards Review*, 4(3), 136–143. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136).
- Godschalk, D., Beatley, T., Berke, P., Brower, D., & Kaiser, E. (1998). Natural hazard mitigation: Recasting disaster policy and planning. Retrieved from https://books.google.com/books?hl=en&lr=&id=J2CDUh5QDGgC&oi=fnd&pg=PR7&ots=axiP9z_LCy&sig=jRKYzWMblovULjyOHArzIx-0fFE.

- Grafakos, S., Viero, G., Reckien, D., Trigg, K., Viguie, V., Sudmant, A., ... Dawson, R. (2020). Integration of mitigation and adaptation in urban climate change action plans in Europe: A systematic assessment. In , vol. 121. Renewable and sustainable energy reviews (p. 109623). Elsevier Ltd.
- Hamad, K., & Kikuchi, S. (2002). Developing a measure of traffic congestion: Fuzzy inference approach. Transportation Research Record: Journal of the Transportation Research Board, 1802(1), 77–85. National Research Council.
- Hopkins, L. D., & Knaap, G. (2018). Autonomous planning: Using plans as signals. Planning Theory, 17(2), 274–295. https://doi.org/10.1177/1473095216669868.
- Horney, J., Nguyen, M., Salvesen, D., Dwyer, C., Cooper, J., & Berke, P. (2017). Assessing the quality of rural hazard mitigation plans in the southeastern United States. *Journal* of Planning Education and Research, 37(1), 56–65. https://doi.org/10.1177/ 0739456X16628605
- Houston. (2020). Super neighborhoods. http://www.houstontx.gov/superneighborh
- Huang, W., & Ling, M. (2018). System resilience assessment method of urban lifeline system for GIS. Computers, Environment and Urban Systems, 71, 67–80. https://doi. org/10.1016/j.compenvurbsys.2018.04.003.
- Huang, X., Gao, J., Buldyrev, S. V., Havlin, S., & Stanley, H. E. (2011). Robustness of interdependent networks under targeted attack. *Physical Review E - Statistical*, *Nonlinear, and Soft Matter Physics*. https://doi.org/10.1103/PhysRevE.83.065101.
- Jenelius, E. (2009). Network structure and travel patterns: Explaining the geographical disparities of road network vulnerability. *Journal of Transport Geography*, 17(3), 234–244. https://doi.org/10.1016/j.jtrangeo.2008.06.002.
- Jenelius, E., & Mattsson, L. G. (2015). Road network vulnerability analysis: Conceptualization, implementation and application. *Computers, Environment and Urban Systems*, 49, 136–147. https://doi.org/10.1016/j.compenyurbsvs.2014.02.003.
- Kaza, N., & Hopkins, L. (2012). Intentional actions, plans, and information systems. International Journal of Geographical Information Science, 26(3), 557–576. https://doi.org/10.1080/13658816.2011.603337.
- Khaghani, F., & Jazizadeh, F. (2020). mD-resilience: A multi-dimensional approach for resilience-based performance assessment in urban transportation. Sustainability, 12 (12), 4879. MDPI AG.
- Kocatepe, A., Ulak, M. B., Kakareko, G., Ozguven, E. E., Jung, S., & Arghandeh, R. (2019). Measuring the accessibility of critical facilities in the presence of hurricane-related roadway closures and an approach for predicting future roadway disruptions. Natural Hazards, 95(3), 615–635. Springer Netherlands.
- Kong, Simonovic, & Zhang. (2019). Resilience assessment of interdependent infrastructure systems: A case study based on different response strategies. Sustainability, 11(23), 6552. MDPI AG.
- Korkali, M., Veneman, J. G., Tivnan, B. F., Bagrow, J. P., & Hines, P. D. H. (2017). Reducing cascading failure risk by increasing infrastructure network interdependence. *Scientific Reports*, 7.
- Laeni, N., van den Brink, M., & Arts, J. (2019). Is Bangkok becoming more resilient to flooding? A framing analysis of Bangkok's flood resilience policy combining insights from both insiders and outsiders. Cities, 90, 157–167. https://doi.org/10.1016/j. cities 2019 02 002
- Lang, W., Chen, T., Chan, E. H. W., Yung, E. H. K., & Lee, T. C. F. (2019). Understanding livable dense urban form for shaping the landscape of community facilities in Hong Kong using fine-scale measurements. *Cities*, 84, 34–45. https://doi.org/10.1016/j. cities.2018.07.003.
- Li, D., Zhang, Q., Zio, E., Havlin, S., & Kang, R. (2015). Network reliability analysis based on percolation theory. *Reliability Engineering and System Safety*, 142, 556–562. https://doi.org/10.1016/j.ress.2015.05.021.
- Li, Q., Dong, S., & Mostafavi, A. (2019). Modeling of inter-organizational coordination dynamics in resilience planning of infrastructure systems: A multilayer network simulation framework. *PLoS One*, 14(11). https://doi.org/10.1371/journal. pone.0224522.
- Li, Q., Dong, S., & Mostafavi, A. (2020). Metanetwork framework for analysis of actorplan-task-infrastructure networks in resilience planning and management. *Natural Hazards Review*, 21(2), Article 04020016.
- Liu, J. L., Han, B., & Cohen, D. A. (2015). Beyond neighborhood food environments: Distance traveled to food establishments in 5 US cities, 2009–2011. Preventing Chronic Disease, 12.
- Liu, R. R., Eisenberg, D. A., Seager, T. P., & Lai, Y. C. (2018). The "weak" interdependence of infrastructure systems produces mixed percolation transitions in multilayer networks. *Scientific Reports*, 8(1), 2111. Nature Publishing Group.
- Lu, P., & Stead, D. (2013). Understanding the notion of resilience in spatial planning: A case study of Rotterdam, the Netherlands. *Cities*, 35, 200–212. https://doi.org/10.1016/j.cities.2013.06.001.
- Lyles, W., Berke, P., & Smith, G. (2016). Local plan implementation: Assessing conformance and influence of local hazard plans in the United States. *Environment* and Planning B, 43(2), 381–400.
- Malecha, M., Masterson, J. H., Yu, S., & Berke, P. (2019). Plan Integration for Resilience Scorecard guidebook: Spatially evaluating networks of plans to reduce hazard vulnerability - Version 2.0. College Station, Texas: Institute for Sustainable Communities, College of Architecture, Texas A&M University. Retrieved from: http://mitigationguide.org/wp-content/uploads/2018/03/Guidebook-2019.Se pt-14 pdf
- Malecha, M. L., Brand, A. D., & Berke, P. R. (2018). Spatially evaluating a network of plans and flood vulnerability using a plan integration for resilience scorecard: A case study in Feijenoord District, Rotterdam, the Netherlands. *Land Use Policy*, 78, 147–157. https://doi.org/10.1016/j.landusepol.2018.06.029.
- Malecha, M. L., Woodruff, S., & Berke, P. R. (2021). Planning to mitigate, or to exacerbate, flooding hazards? Evaluating a Houston, Texas, network of plans in

- place during Hurricane Harvey using a Plan Integration for Resilience Scorecard.
- Maltinti, F., Melis, D., & Annunziata, F. (2012). Road network vulnerability: A review of the literature. https://doi.org/10.1061/41204(426)83.
- Miles, S. B., Burton, H. V., & Kang, H. (2019). Community of practice for modeling disaster recovery. *Natural Hazards Review*, 20(1), Article 04018023. https://doi.org/ 10.1061/(ASCE)NH.1527-6996.0000313.
- Miller, M., & Baker, J. W. (2016). Coupling mode-destination accessibility with seismic risk assessment to identify at-risk communities. *Reliability Engineering and System* Safety, 147, 60–71. https://doi.org/10.1080/01944360208976274.
- Mitsova, D., Escaleras, M., Sapat, A., Esnard, A. M., & Lamadrid, A. J. (2019). The effects of infrastructure service disruptions and socio-economic vulnerability on hurricane recovery. Sustainability, 11(2), 516.
- Mitsova, D., Sapat, A., Esnard, A. M., & Lamadrid, A. J. (2020). Evaluating the impact of infrastructure interdependencies on the emergency services sector and critical support functions using an expert opinion survey. *Journal of Infrastructure Systems*, 26 (2), Article 04020015. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000548.
- Mostafizi, A., Dong, S., & Wang, H. (2017). Percolation phenomenon in connected vehicle network through a multi-agent approach: Mobility benefits and market penetration. Transportation Research Part C: Emerging Technologies, 85, 312–333.
- Mostafizi, A., Wang, H., Cox, D., Cramer, L. A., & Dong, S. (2017). Agent-based tsunami evacuation modeling of unplanned network disruptions for evidence-driven resource allocation and retrofitting strategies. *Natural Hazards*, 88(3), 1347–1372. https://doi.org/10.1007/s11069-017-2927-y.
- National Research Council. (2012). Disaster resilience: A national imperative. Washington, D.C.: National Academies Press.
- National Research Council. (2014). Reducing coastal risk on the east and gulf coasts. Washington, D.C.: The National Academies Press.
- National Response Plan. (December 2004). U.S. Department of Homeland Security.
 Sadiq, A. A., & Noonan, D. S. (2015). Flood disaster management policy: An analysis of the United States Community Ratings System. Journal of Natural Resources Policy Research, Routledge, 7(1), 5–22.
- Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering and System Safety*, 121, 43–60. https://doi.org/10.1016/j.ress.2013.06.040.
- Ouyang, M. (2017). A mathematical framework to optimize resilience of interdependent critical infrastructure systems under spatially localized attacks. *European Journal of Operational Research*, 262(3), 1072–1084. https://doi.org/10.1016/j.eior.2017.04.022.
- Pathak, A., Zhang, L., & Ganapati, N. E. (2020). Understanding multisector stakeholder value dynamics in hurricane Michael: Toward collaborative decision-making in disaster contexts. *Natural Hazards Review*, 21(3), Article 04020032. https://doi.org/ 10.1061/(ASCE)NH.1527-6996.0000400.
- Ruj, S., & Pal, A. (2014). Analyzing cascading failures in smart grids under random and targeted attacks. In *Proceedings - international conference on advanced information* networking and applications, AINA (pp. 226–233). Institute of Electrical and Electronics Engineers Inc.
- Shao, S., Huang, X., Stanley, H. E., & Havlin, S. (2015). Percolation of localized attack on complex networks. New Journal of Physics, 17. https://doi.org/10.1088/1367-2630/ 17/2/023049.
- Song, J., Chang, Z., Li, W., Feng, Z., Wu, J., Cao, Q., & Liu, J. (2019). Resilience-vulnerability balance to urban flooding: A case study in a densely populated coastal city in China. Cities, 95, Article 102381. https://doi.org/10.1016/j.cities.2019.06.012
- Sullivan, J. L., Novak, D. C., Aultman-Hall, L., & Scott, D. M. (2010). Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A: Policy and Practice*, 44(5), 323–336. https://doi.org/10.1016/j. tra.2010.02.003.
- Sun, W., Bocchini, P., & Davison, B. D. (2020). Resilience metrics and measurement methods for transportation infrastructure: The state of the art. In Sustainable and resilient infrastructure. Taylor and Francis Inc.
- Tahmasbi, B., & Haghshenas, H. (2019). Public transport accessibility measure based on weighted door to door travel time. *Computers, Environment and Urban Systems*, 76, 163–177. https://doi.org/10.1016/j.compenvurbsys.2019.05.002.
- Taylor, M. A. P., Sekhar, S. V. C., & D'Este, G. M. (2006). Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics*, 6(3–4), 267–291. https://doi.org/10.1007/s11067-006-9284-9.
- Torrens Resilience Institute. (2015). A way to measure community disaster resilience: Community disaster resilience scorecard toolkit, version 2. Retrieved from http://www.flinders.edu.au/fms/documents/NP1314_Revised_TRI%20Toolkit%20and%20Scorecard%20Version%202.pdf.
- Tsou, K. W., Hung, Y. T., & Chang, Y. L. (2005). An accessibility-based integrated measure of relative spatial equity in urban public facilities. *Cities*, 22(6), 424–435. https://doi.org/10.1016/j.cities.2005.07.004.
- U.S. Department of Transportation. (2014). FHWA order 5520 Transportation system preparedness and resilience to climate change and extreme weather events. Retrieved April 6, 2020, from https://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm.
- Ulak, M. B., Kocatepe, A., Ozguven, E. E., Horner, M. W., & Spainhour, L. (2017). Geographic information system-based spatial and statistical analysis of severe crash hotspot accessibility to hospitals. *Transportation Research Record: Journal of the Transportation Research Board, 2635*(1), 90–97. SAGE Publications Ltd.
- United Nations General Assembly. (2015). United Nations world conference on disaster reduction—Sendai framework for disaster reduction 2015–2030. Sendai, Japan: Author. Retrieved from http://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf.

- United Nations Office for Disaster Risk Reduction. (2015). Disaster resilience scorecard for cities. Retrieved from http://www.unisdr.org/2014/campaign-cities/Resilience %20Scorecard%20V1.5.pdf.
- United Nations Office for Disaster Risk Reduction. (2017). Disaster statistics: Total damages: All continents. Geneva: United Nations Office for Disaster Risk Reduction. http://www.emdat.be/disaster_trends/index.html.
- Vermont Natural Resources Council. (2013). Resilient Communities Scorecard.

 Montpelier, VT. Retrieved from http://vnrc.org/wp-content/uploads/2013/06/Cover-and-Credits.pdf.
- Vugrin, E. D., Warren, D. E., & Ehlen, M. A. (2011). A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane. *Process Safety Progress*, 30(3), 280–290. John Wiley & Sons, Ltd.
- Wan, C., Yang, Z., Zhang, D., Yan, X., & Fan, S. (2018). Resilience in transportation systems: A systematic review and future directions. *Transport Reviews*, 38(4), 479–498. https://doi.org/10.1080/01441647.2017.1383532\.
- Wang, W., Yang, S., Stanley, H. E., & Gao, J. (2019). Local floods induce large-scale abrupt failures of road networks. *Nature Communications*, 10(1). https://doi.org/ 10.1038/s41467-019-10063-w.
- Weilant, S., Strong, A., & Miller, B. M. (2019). Incorporating resilience into transportation planning and assessment. *Transportation Research Record*. https://www.rand.org/content/dam/rand/pubs/research_reports/RR3000/RR303 8/RAND RR3038.pdf.

- Widener, M. J., Farber, S., Neutens, T., & Horner, M. (2015). Spatiotemporal accessibility to supermarkets using public transit: An interaction potential approach in Cincinnati, Ohio. *Journal of Transport Geography*, 42, 72–83. Elsevier Ltd.
- Winfree, G. D. (2019). The need for resilience: Preparing America's transportation infrastructure for climate change. U.S House of Representatives Committee on Science, Space and Technology, Subcommittee on Investigations and Oversight. retrieve 2020-03-15, URL: https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=109554.
- Xiao, H., & Yeh, E. M. (2011). Cascading link failure in the power grid: A percolationbased analysis. In *IEEE international conference on communications*.
- Yu, S., Brand, A. D., & Berke, P. (2020). Making room for the river: Applying a plan integration for resilience scorecard to a network of plans in Nijmegen, the Netherlands. *Journal of the American Planning Association*, 1–14. https://doi.org/ 10.1080/01944363.2020.1752776.
- Zeng, Z., Lan, J., Hamidi, A. R., & Zou, S. (2020). Integrating Internet media into urban flooding susceptibility assessment: A case study in China. *Cities*, *101*, Article 102697. https://doi.org/10.1016/j.cities.2020.102697.
- Zhang, D., Çetinkaya, E. K., & Sterbenz, J. P. G. (2013). Robustness of mobile ad hoc networks under centrality-based attacks. In International congress on ultra modern telecommunications and control systems and workshops (pp. 229–235). IEEE Computer Society.
- Zhang, W., Wang, N., & Nicholson, C. (2017). Resilience-based post-disaster recovery strategies for road-bridge networks. Structure and Infrastructure Engineering, 13(11), 1404–1413. https://doi.org/10.1080/15732479.2016.1271813.