Network-based Assessment of Resilience of Road Systems

Naiyu Wang1, Weili Zhang2

Abstract:
Transportation infrastructure has been identified by the US Department of Homeland Security as one of sixteen critical infrastructure systems essential to the well-being of modern society. In this study, we propose a resilience-based framework for mitigating risk to road systems, considering both community and regional scales. We utilize recent developments in modern network theory to introduce a novel indicator based on system reliability and network connectivity to measure resilience and resilience improvement of a road transportation network. Our formulation systematically integrates the network topology, redundancy level, traffic patterns, and functionality during a community’s post-disaster recovery period, includes structural reliability (failure probability) of individual bridges in the network, and permits risk mitigation alternatives for improving transportation network resilience to be compared on a common basis. We propose a project ranking mechanism for identifying and prioritizing bridge maintenance or retrofit projects that are critical for effective pre-disaster risk mitigation of bridge systems. We provide a decision methodology to select optimal solutions among possible alternatives when the prospect of new construction offers opportunities to improve the resilience of the network by altering its existing topology. Finally, we conclude with an illustration of this resilience-based risk mitigation framework using a hypothetical bridge network susceptible to seismic hazards.

Keywords: Bridges; Civil infrastructure systems; Decision optimization; Resilience; Risk mitigation; System reliability; Transportation networks.

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1. Introduction

The resilience of robust, large-scale, interdependent civil infrastructure networks, including transportation systems, utilities, telecommunication facilities, and social networks, individually and collectively play a major role in determining the resilience of a community as a whole. The performance of transportation networks, in particular, is critical because post-disaster restoration of virtually all other facilities and lifelines in a community depends on people and equipment being able to move to the sites where damage has occurred. Highway bridges typically are the vulnerable links in road transportation systems and require especially effective risk mitigation strategies aimed at improving the resilience of transportation systems against future natural disasters.

Resilience of a system is its ability to withstand or adapt to external shocks and to recover from such shocks efficiently and effectively (Timmerman, 1981; Pimm, 1984). In the case of civil infrastructure, resilience is often associated with four attributes (Bruneau et al 2003; Chang and Shinozuka, 2004): robustness - the ability to withstand an extreme event and deliver a certain level of service even after the occurrence of that event; rapidity - to recover the desired functionality as quickly as possible; redundancy - the extent to which elements and components of a system can be substituted for one another; and resourcefulness - the capacity to identify problems, establish priorities, and mobilize personnel and financial resources after an extreme event. These attributes are illustrated in Figure 1a; all are characterized by considerable uncertainties. Many research studies have discussed the resilience of systems other than civil infrastructures, including ecosystems (Holling, 1973; Walker and Salt, 2006; Leichenko, 2011), topologies of computer networks (Scheffel, et al 2006; Simonis, 2006), communication networks (Sterbenz et al 2010; Zhu and Basar, 2015), and socio-economic systems (Ross, 2007; Martin, 2012).

Strategic investments and mitigation strategies can gradually improve the resilience of a system against future disasters, as indicated in Figure 1b. For bridge systems, such risk mitigation strategies often involve structural rehabilitation or retrofit. However, the engineering processes of retrofitting bridges are extremely costly and time consuming, and are often constrained by limited financial and human resources. Consequently, systematic retrofit prioritization is a critical element of an effective risk mitigation framework for enhancing resilience road transportation systems. Such a framework requires not only a consideration of the physical condition and structural vulnerability of each individual bridge in the inventory (e.g. Shinozuka et al, 2000; Padgett and DesRoches, 2009) but also a systems perspective that takes into account the overall pre- and post- disaster operation and functionality of the network as a whole (e.g. Sohn et al, 2003; Nagurney and Qiang, 2007; Peeta et al, 2010). As examples, Shiraki et al
(2007) combined bridge fragility curves with the network user-equilibrium functions to estimate the total road network delay due to earthquake-introduced damages; Bocchini and Frangopol (2013a) proposed a bridge network maintenance scheduling approach that incorporated both individual bridge reliabilities and the network connectivity into the optimization formulation.

While structural reliability (failure probability) is a well-accepted measure for vulnerability of individual bridges under operating or natural hazards, the performance of a transportation system must be...
measured by different metrics. Many researchers have quantified network performance based on network service functions, e.g., flow capacity (Nagurney and Qiang, 2007; Lee et al., 2011), connectivity (Chen et al. 2002; Clark and Watling, 2005; GUiikema andardoni, 2009; Bocchini and Frangopol, 2013a; Kurtz et al., 2015), and travel time reliability (Asakura and Kashiwadani, 1995; Chen et al., 2007; Zhang and Wang, 2015). However, these metrics are mainly applicable to a transportation system operating under normal service conditions and do not reflect the resilience of the system under disruptive natural or man-made hazards. Resilience-based infrastructure management is a multi-stage process, beginning with pre-disaster preparedness and mitigation, focusing on long-term measures for risk reduction and extending to post-disaster response and recovery. Accordingly, different metrics would be appropriate for risk management decisions at different stages of the resilience spectrum illustrated in Figure 1. For example, Peeta et al (2010) used post-disaster connectivity and traversal cost between multiple origin-destination pairs in a network as the basis for pre-disaster investment decisions; Morlok and Chang (2004) proposed capacity flexibility to reflect a transportation system’s ability to adapt to changes in traffic patterns caused by natural disasters; Chang and Nojima (2001) introduced the notion of network coverage and transport accessibility as the performance measures for post-disaster network recovery; and Ip and Wang (2011) suggested that pathway redundancy between all origin-destination pairs be used as a resilience measure for transportation networks. These performance measures, however, do not directly reflect the network resilience in terms of its ability to withstand and to recover from hazard-induced interruptions (earthquakes, floods, terrorist attacks, etc.). Furthermore, none of these studies have attempted to quantify the uncertainties associated with these performance measures.

2. Organization and Highlights of the Paper

In this paper, we propose a novel indicator based on network reliability and connectivity to measure resilience of road/bridge networks, which allows resilience-based risk mitigation alternatives for transportation systems to be compared on a common basis. The resilience indicator is based on modern graph theory, in a formulation which systematically integrates the network topology, system redundancy level, traffic patterns, functionality during community’s post-disaster recovery and structural reliability of each individual bridge. Based on this resilience indicator, we next introduce a project ranking mechanism for identifying and prioritizing bridge retrofit projects that are critical for effective pre-disaster risk mitigation of existing road/bridge networks. Finally, we provide a decision methodology to select optimal solutions among possible alternatives when the prospect of new construction offers an opportunity to improve the resilience of the network by altering its existing topology. We conclude with an illustration of our network-based resilience assessment framework, considering a hypothetical networked system of 37 bridges that are susceptible to seismic hazard.
3. Transportation Network Resilience Indicator

The fundamental purpose of a transportation system is to carry traffic from origins to destinations. The resilience of such a system is reflected in its ability to continue to fulfill this purpose in the event of natural or man-made disasters. If numerous bridges in a community road system are damaged by an earthquake or a flood, the repair of those bridges often depends on the availability of other financial and human resources which may not be immediately available following the disaster. Thus, the existence of redundant alternative paths between all origin-destination (O-D) pairs in the community transportation system, especially between “critical” pairs, is crucial for the continued operation of the transportation system as well as the recovery of the community, and therefore is an essential characteristic of a resilient transportation network.

Accordingly, by extending the concept suggested by Ip and Wang (2011), we define the resilience indicator of the transportation system as the weighted average number of reliable independent pathways (IPWs) between any O-D pairs in the transportation network. A pathway between an O-D pair usually consists of several links that represent roads, with or without bridges, which are connected in series. Two pathways between the same O-D pair are considered as independent, i.e. IPWs, if they do not share any common road links. The process of identifying all IPWs in a transportation network will be discussed later. Note that alternative IPWs between a given O-D pair do not have identical impacts on the network resilience; pathways that are more structurally reliable (their probabilities of failure due to severe hazards are less) contribute more to the resilience of the network as whole. Therefore, the resilience indicator, as formulated subsequently, depends on the weighted reliabilities of the IPWs.

Introducing the terminology of graph theory (Gibbons, 1985), let $G = (V, A)$ denote the road network, where $V = \{1, 2, ..., n\}$ is the set of nodes that represents major road intersections and economic hubs and key destinations in a community, and $A = \{1, 2, ..., m\}$ is the set of arcs (links). The resilience of the network, $\mathcal{R}(G)$, as defined above, can be written as:

$$\mathcal{R}(G) = \sum_{i=1}^{m} w_i r_i$$  \hspace{1cm} (1)

A critical O-D pair is one that connects facilities, such as hospitals, fire stations, and communication centers, which are essential for post-disaster community recovery.
where \( w_i = \) weighting factor applied to individual node \( i \in V \), \( \sum_{i=1}^{n} w_i = 1 \), and \( r_i = \) the average number of reliable IPWs between node \( i \) and any other \( n - 1 \) nodes in the network, as expressed in Eq. (2):

\[
    r_i = \frac{1}{n-1} \sum_{j=1, j \neq i}^{n} K_{(i,j)} \sum_{k=1}^{w_k(i,j)} R_k(i,j)
\]

in which \( K_{(i,j)} \) = total number of IPWs between nodes \( i \) and \( j \); \( R_k(i,j) \) = reliability of \( P_k(i,j) \), the \( k \)th IPW between node \( i \) and node \( j \); \( w_k(i,j) \) = weighting factor applied to IPW \( P_k(i,j) \), and for all \( K_{(i,j)} \) IPWs between nodes \( i \) and \( j \), \( \sum_{k=1}^{w_k(i,j)} R_k(i,j) = K_{(i,j)}. \) Weighting factors \( w_i \) and \( w_k(i,j) \) will be discussed in detail below. Each IPW, \( P_k(i,j) \), usually consists of several road links connected in series. Let \( l \) denote the individual road links and \( q_l \) denote the reliability of \( l \); thus, for a system demand that is positively correlated, the product of the reliabilities\(^4\) of all road links included in \( P_k(i,j) \) provides a lower bound on system reliability, \( R_k(i,j) \):

\[
    R_k(i,j) = \prod_{\forall l \in P_k(i,j)} q_l
\]

Combining Eqs (2) and (3), the resilience of the road network defined in Eq. (1) is then:

\[
    \Re(G) = \sum_{i=1}^{n} \frac{1}{w_i} \sum_{j=1, j \neq i}^{n} K_{(i,j)} \sum_{k=1}^{w_k(i,j)} R_k(i,j) \prod_{\forall l \in P_k(i,j)} q_l
\]

Two weighting factors, \( w_i \) and \( w_k(i,j) \), appear in Eq. (4). Factor \( w_i \) applies to nodes; it is inversely proportional to the shortest distance from node \( i \) to the nearest emergency response facility in the community, reflecting the relative importance of the node \( i \) being connected in the context of community post-disaster emergency response. Let \( E \), a subset of \( V \), denote the set of nodes in the network where emergency response facilities are located, \( N = \) the set of nodes that do not belong \( E \), and \( L_{P_k(i,j \in E)} = \) the length of \( P_k(i,j) \) where \( j \in E \). We then evaluate \( w_i \) as:

\[
    w_i = \frac{\Omega_i}{\sum_{j=1}^{n} \Omega_j}
\]

\(^4\)This assumption implies that the link reliabilities are statistically independent. Although this assumption may not hold exactly for natural hazards with large geographic footprints, it is well-known from systems reliability theory that this assumption is conservative, especially for bridges that are widely separated in the system.
where

\[ \Omega_i = \begin{cases} 
1 / \min\{L_{P_k(i,j) | k = 1, 2 \ldots K(i,j)}\} & i \in N \\
1 & i \in E 
\end{cases} \]

As noted previously, the sum of \( w_i \) for all the nodes in the network equals 1.

The other weighing factor \( w_k(i,j) \) in Eq. (4) applies to IPWs; it is related to both the average daily traffic (ADT) and the length of the IPW, and reflects the relative impact that this pathway has on people’s normal life activities and the local economy. Pathways between any given O-D pair that have shorter length and carry larger traffic flow contribute more to the network functionality and should be weighted more heavily in quantifying the network resilience. Let \( T_l \) denote the ADT of road link \( l \in P_k(i,j) \). Define \( T_{P_k(i,j)} \), the ADT of IPW \( P_k(i,j) \), as the minimum ADT of all road links on that pathway:

\[ T_{P_k(i,j)} = \min\{T_l | l \in P_k(i,j)\} \]

The normalized ADT of the path is then defined as:

\[ T'_{P_k(i,j)} = \frac{T_{P_k(i,j)}}{\sum_{k=1}^{K(i,j)} T_{P_k(i,j)}} \times K_{(i,j)} \] \hspace{1cm} (8)

Note that for any node pair \((i,j)\), \( \sum_{k=1}^{K(i,j)} T'_{P_k(i,j)} = K_{(i,j)} \). Similarly, let \( L_l \) = the length of the road link \( l \); then the length of the IPW \( P_k(i,j) \) is simply the summation of the lengths of all road links within that path:

\[ L_{P_k(i,j)} = \sum_{l \in P_k(i,j)} L_l \]

Finally, let \( L_{\text{max}}(i,j) \) = maximum of all \( L_{P_k(i,j)} \) for a given O-D pair \((i,j)\); then the normalized length of the path is:

\[ L'_{P_k(i,j)} = \frac{L_{\text{max}}(i,j)}{L_{P_k(i,j)} \times \sum_{k=1}^{K(i,j)} (L_{\text{max}}(i,j)/L_{P_k(i,j)})} \times K_{(i,j)} \] \hspace{1cm} (10)

Note that for any node pair \((i,j)\), \( \sum_{k=1}^{K(i,j)} L'_{P_k(i,j)} = K_{(i,j)} \). Using Eqs (8) and (10), we define the aggregated pathway weighting factor \( w_k(i,j) \) as:

\[ w_k(i,j) = \frac{T'_{P_k(i,j)} \times L'_{P_k(i,j)}}{T_{P_k(i,j)} L_{P_k(i,j)}} \]

\[ w_k(i, j) = \frac{1}{2} (L'_{pk}(i, j) + T''_{pk}(i, j)) \]  \hspace{1cm} (11)

The summation of all \( w_k(i, j) \) for a given O-D pair \((i, j)\) equals \( K_{(i,j)} \), the total number of IPWs between nodes \( i \) and \( j \).

The node weighing factor \( w_i \) and IPW weighting factor \( w_k(i, j) \), so defined, not only ensure that all nodes and links in the network are properly weighted in the resilience indicator based on their individual attributes (topology, traffic patterns, and functionality during a community’s post-disaster recovery as well as structural reliability of individual bridges), but also preserve the physical meaning of the indicator - the weighted average number of reliable IPWs between all O-D pairs in the road network. The role that a transportation system will play before, during and after a disaster will vary uniquely for every community. Stakeholders of communities of different size, population and social-economic attitudes and vulnerabilities are likely to show different values and preferences when evaluating the resilience of their transportation system. Weighting factors, formulated as above, provide a transparent method to incorporate and properly weigh other desired network attributes, in addition to those discussed above, in the network resilience quantification. Figure 2 displays the algorithm for computing the resilience indicator for a road network as formulated above. It is apparently to observe that the independent pathways are non-unique, which depends on the algorithm or process to search IPWs. In this work, we apply Dijkstra’s algorithm (Skiena, 1990) to find a succession of shortest paths as the IPWs. The procedure is highlighted in Figure 2 with dashed-line box.
Input a bridge network

Compose nodes pair \((i, j)\)

Are all nodes pair computed?

Search for the shortest path between nodes pair \((i, j)\) using Dijkstra’s Algorithm

Is shortest path found?

Yes

Store the shortest path \(P_k(i, j), L_{P_k(i, j)}\), and \(T_{P_k(i, j)}\)

Remove the arcs in \(P_k(i, j)\)

Normalize \(L_{P_k(i, j)}, T_{P_k(i, j)}\) to obtain \(L'_{P_k(i, j)}, T'_{P_k(i, j)}\) according to Eqs. (8) and (9)

Calculate \(R_k(i, j)\) according to Eq. (3)

Are all nodes pair computed?

Compute \(r_i\) according to Eq. (2), and \(\Omega_i\) and \(w_i\) to Eqs. (6) and (7)

Are all nodes computed?

Compute the resilience of the network according to Eq. (4)

Figure 2. Evaluation of network resilience indicator


4. Reliability of Bridges (Links) in a Community Transportation System

An important step to quantify the resilience indicator is to properly assign link reliabilities. Since bridges are generally more vulnerable to natural hazards than roads, it is reasonable to assume that the link reliability equals the minimum reliability of bridges located in that link. The reliability of an individual bridge can be evaluated using fragility analyses associated with damage states of interest [e.g. using platform HAZUS-MH MR4 (DHS 2009)]. It should be recognized that hazardous events with large footprints introduce spatial and temporal correlations to the demands on the community infrastructure (Adachi and Ellingwood, 2008; Jayaram and Baker, 2009). Common building practices and code enforcement within a community also introduce positive correlation in structural response above and beyond that introduced by the hazard (Vitoontus and Ellingwood, 2013; Bonstrom and Corotis 2014). Such correlations depend on the stochastic variability in the hazard demand, the number of bridges and their locations, and their susceptibility to damage if the hazardous event occurs. When bridges are considered as components of a transportation system, this correlation need to be taken into consideration in evaluating bridge reliabilities with respect to an interested hazard scenario (Lee and Kiremidjian, 2007; Bocchini and Frangopol, 2011). The resilience indicator calculated using assigned link (bridge) reliabilities is hazard specific because these link reliabilities are hazard specific.

Bridge fragility assessment has been shown to be an important ingredient for seismic risk assessment of transportation infrastructure (Padgett and DesRoches, 2009). The current research is focused on transportation network modeling; such networks may contain many different types of bridges and, thus, bridge fragility modeling is outside the scope of the current effort. However, a practical assessment of the integrity of any transportation network should contain specific fragility models for the key bridges in the network. In the subsequent examples, we use plausible estimates of failure probabilities for generic bridge types.

5. Formulation of Optimal Risk Mitigation Strategies

The quantitative resilience indicator introduced in Section 3 provides a common basis for alternative risk mitigation strategies to be evaluated and compared on a rational basis. Possible pre-disaster risk mitigation strategies to improve road network resilience include retrofitting existing bridges (links) or altering the network topology through new construction. In either case, the formulation of the decision process is the same: to make selections from a set of candidate links (including bridges), representing either existing or potential new construction, to maximize the network resilience and simultaneously minimize the associated cost.

Suppose the set of candidates is represented by \( S = \{s_1, s_2 \ldots s_s \} \) and the corresponding cost of each is \( c = \{c_1, c_2 \ldots c_s \} \). Let \( x_t \in X \), where \( t = 1, 2 \ldots s \), denote the decision variables as below.

\[
    x_t = \begin{cases} 
        1, & s_t \in S \text{ is selected} \\
        0, & \text{otherwise}
    \end{cases}
\]  

(12)

Since the risk mitigation strategy (or decision) represented by \( X \) will upgrade the existing network, we rewrite all the parameters of the upgraded network in the form of argument \( X \), e.g., \( \Re(G(X)) \), \( w_i(X) \), \( r_t(X) \) and \( P_k(i,j|X) \). Furthermore, some network parameters are uncertain and are treated as random variables in the problem formulation; these variables will be represented with argument \( \xi \). Thus, the first objective of the decision process is to maximize the network resilience:

\[
    \max \Re(G(X, \xi)) = \sum_{i=1}^{n} w_i(X) r_t(X, \xi)
\]  

(13)

Let \( \theta(X) \) denote the cost associated with decision \( X \); the second objective function is to minimize the total cost:

\[
    \min \theta(X, \xi) = \sum_{t=1}^{s} c_t(\xi) x_t
\]  

(14)

Eqs. (13) and (14) pose a nontrivial multi-objective optimization problem, and a single solution that simultaneously optimizes these two competing objectives, i.e., maximize the network resilience and minimizing cost associated with mitigation strategies, does not exist. However, a (possibly infinite) number of Pareto-optimal solutions does exist, which allows the tradeoff between the competing objectives and the subjective preferences of a decision maker to be factored in decision process. We use a Genetic Algorithm (GA) (Deb et al, 2002) to search for the Pareto frontier, coupled with Monte Carlo Simulation (MCS) to take uncertainties into consideration in the optimization process in the subsequent case study. Since the parameter values have significant effects on GA performance (Eiben and Smit, 2012), through rigorous test on tuning parameters, the mutation parameter, crossover rate, population size are set as 0.1, 0.7 and 100, respectively. The maximum number of iterations is 1000, and the early termination criterion is 50, which means the program will stop if no better solution is found in consecutive 50 iterations.
6. Illustration – Resilience of Transportation Network Exposed to Seismic Hazards

In this section, the role of the network resilience indicator and the application of the decision methodology for risk mitigation are illustrated with a hypothetical road network exposed to a severe earthquake. Two scenarios are discussed: (1) establishing priorities for identifying and retrofitting bridges that are critical for transportation network performance prior to the occurrence of the earthquake under budget constraints, and; (2) selecting among possible alternatives when the prospect of new construction offers an opportunity to improve the resilience of the network by altering its existing topology.

6.1 Road/Bridge Network

Figure 2 illustrates a hypothetical community road system, with 37 links representing the roads and 30 nodes representing the major road intersections and economic hubs in the community. The community emergency response facilities (e.g. fire stations, hospitals, police, etc.) are located at Nodes 9 and 17. For simplicity, we further assume that every road contains exactly one bridge. This assumption can be easily relaxed, if necessary. It is found that, although the number of pathways in a road network between an O-D pair can be very large, the number of IPWs is often very limited. If all the bridges in the community are in "as new" condition and have reliabilities under service loads are assumed equal to 0.999, we find the upper bound of the network resilience (as formulated in Section 3) is 1.70, which means that on average there are 1.70 independent pathways (a measure of redundancy) between any O-D pair in the community road network under normal operational conditions.

We now assume that a very rare earthquake occurs, with magnitude Mw equal to 7 and epicentral distance approximately 40 km from the centroid of the network illustrated in Figure 2 (close to Node 13). For illustrative purposes, we assume that out of the 37 bridges, 19 are steel (S) and 18 are reinforced concrete (RC). To reflect the diversity of bridge construction (including bridge configuration, material and area) within the network, we assume that the mean reliabilities of the 19 steel bridges and 17 RC bridges under seismic action (summarized in Table 2) are 0.75 and 0.65, respectively; further, that the mean reliabilities of the individual bridges reflect the correlation in their structural performance due to common hazard and similar construction materials and practices. This correlation decreases exponentially with an increase in the separation distance between bridges, i.e. \( \rho_{ij} = \exp\left( -l/L_c \right) \), where \( l \) is the separation distance between bridges \( i \) and \( j \), and \( L_c \) is the correlation length which is equal to the largest distance between two bridges in the network. To reflect the epistemic uncertainty in bridge performance,
the reliabilities for each bridge are described by a normal distribution, with a coefficient of variation of 0.07 in all cases. This modeling approach results in bridge portfolio in the network that represents a diversity in bridge construction. In addition, the retrofit cost for each bridge is also modeled with a normal distribution, assuming that the mean cost is a function of the bridge deck area and its structural reliability (Fragkakis and Lambropoulos, 2004). The reliability, ADT and repair cost of each bridge are tabulated in Table 2. The distributions used to model the uncertainty in these parameters in MCS are summarized in Table 3.

Figure 4 illustrates the histogram of the residual network resilience, obtained from 1000 Monte Carlo simulations of the network performance, which provides a baseline for the effect of alternative risk mitigation strategies to be evaluated in the subsequent section. The mean resilience of the current network with respect to the considered hazard scenario, without taking any actions to mitigate risk, is 0.61, and the coefficient of variation (COV) is equal to 0.22. Thus, if the scenario earthquake were to occur, there is a 39% chance that the traveler will not be able to get to a destination from an origin, and thus some areas in the community may become isolated from one another following the earthquake.

Figure 3. Hypothetical Bridge Network
### Table 2. Mean Values of Network Parameters

<table>
<thead>
<tr>
<th>Bridge ID</th>
<th>Construction Type</th>
<th>Reliability</th>
<th>ADT</th>
<th>Cost (Unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RC</td>
<td>0.66</td>
<td>2200</td>
<td>3.57</td>
</tr>
<tr>
<td>2</td>
<td>RC</td>
<td>0.76</td>
<td>1900</td>
<td>3.82</td>
</tr>
<tr>
<td>3</td>
<td>S</td>
<td>0.82</td>
<td>2000</td>
<td>4.34</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>0.88</td>
<td>1500</td>
<td>4.17</td>
</tr>
<tr>
<td>5</td>
<td>RC</td>
<td>0.55</td>
<td>1900</td>
<td>4.87</td>
</tr>
<tr>
<td>6</td>
<td>S</td>
<td>0.84</td>
<td>2200</td>
<td>3.49</td>
</tr>
<tr>
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<td>S</td>
<td>0.77</td>
<td>700</td>
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<tr>
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<td>S</td>
<td>0.75</td>
<td>900</td>
<td>4.66</td>
</tr>
<tr>
<td>27</td>
<td>S</td>
<td>0.80</td>
<td>600</td>
<td>4.46</td>
</tr>
<tr>
<td>28</td>
<td>RC</td>
<td>0.71</td>
<td>800</td>
<td>3.33</td>
</tr>
<tr>
<td>29</td>
<td>RC</td>
<td>0.65</td>
<td>1400</td>
<td>4.86</td>
</tr>
<tr>
<td>30</td>
<td>RC</td>
<td>0.67</td>
<td>2800</td>
<td>3.45</td>
</tr>
<tr>
<td>31</td>
<td>RC</td>
<td>0.69</td>
<td>1900</td>
<td>3.08</td>
</tr>
<tr>
<td>32</td>
<td>RC</td>
<td>0.75</td>
<td>2900</td>
<td>3.74</td>
</tr>
<tr>
<td>33</td>
<td>RC</td>
<td>0.79</td>
<td>1300</td>
<td>4.50</td>
</tr>
<tr>
<td>34</td>
<td>RC</td>
<td>0.69</td>
<td>900</td>
<td>4.47</td>
</tr>
<tr>
<td>35</td>
<td>RC</td>
<td>0.72</td>
<td>2200</td>
<td>3.36</td>
</tr>
<tr>
<td>36</td>
<td>RC</td>
<td>0.83</td>
<td>700</td>
<td>4.46</td>
</tr>
<tr>
<td>37</td>
<td>RC</td>
<td>0.73</td>
<td>3000</td>
<td>5.15</td>
</tr>
</tbody>
</table>
### Table 3. Statistics of the Network Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Notation</th>
<th>Distribution</th>
<th>Mean</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual Bridge Reliability</td>
<td>𝑞</td>
<td>Normal</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Average Daily Traffic (ADT)</td>
<td>𝑇</td>
<td>Uniform</td>
<td>As tabulated in Table 2</td>
<td>0.53</td>
</tr>
<tr>
<td>Renewal Cost</td>
<td>𝑐</td>
<td>Normal</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 4. Histogram of Network Resilience before Retrofit](image)

#### 6.2 Improving network resilience by strengthening critical bridges

If limited resources are available for hazard mitigation through bridge retrofitting, it is critical to allocate those resources within the distributed network in such a way that the overall resilience of the network is maximized. The resilience indicator introduced in Section 3 can serve as a criterion to measure the effectiveness of the project selections and prioritizations. Since there are 37 bridges in the network and each can be either selected or not selected for retrofit, the solution space has $2^{37}$ different combinations. As discussed previously, the GA is an evolutionary approach to identify near-optimal solutions in a
reasonable timeframe without exploring all possible combinations, and is used to solve this multi-objective optimization problem as formulated in Section 5. We assume that retrofit will bring the bridge’s reliability back to 0.999, the value previous to the earthquake scenario.

Figure 5 shows the tradeoff between network resilience and financial investment in risk mitigation, with the triangular markers representing the collection of optimal solutions (Pareto Frontier) when resilience and retrofitting cost (measured in non-dimensional cost units) are considered as competing objectives. With a total of 150 cost units, the alternative shown at the top right corner of the figure selects all 37 bridges for retrofit and the corresponding network resilience increases to the pre-earthquake value of 1.7, as all bridges are upgraded to the “near-perfect” hazard-resilient condition. Four solutions on the Pareto Frontier, marked as I, II, III and IV in Figure 5, are detailed in Table 4 for further examination. Generally speaking, a larger financial investment will lead to more bridges being selected for retrofit and, consequently, a more resilient network. For instance, Solution I identifies seven bridges in the network as having retrofit priority, with a budget of 25 cost units, resulting a network resilience of 0.76. In contrast, Solution III indicates that with a budget of 86 cost units, 22 bridges can be selected for retrofit, leading to a network resilience is 1.23, which is a 101% increase over the pre-retrofit network resilience of 0.61. Figure 6 compares the network resilience before and after the retrofit associated with Solution III when uncertainties are considered in the evaluation.

Table 4 reveals that the increase in the number of selected bridges from Solution I to Solution IV is not simply due to adding more bridges to the selected group associated with a lower budget. The likelihood of some bridges, e.g. bridges 11 and 13, being selected increases as the budget increases. Other bridges, e.g. bridges 4 and 33, are selected initially when the budget is low; however, they are deselected as the budget increases because a neighboring bridge on an alternative path may become a more cost-effective candidate for improving the overall network resilience. Finally, bridges 5 and 17 are always selected in optimal retrofit solutions because, when compared with other bridges, they both: 1) have much lower than average structural reliabilities (0.55 and 0.61); 2) carry heavy ADT (1900 and 2500); 3) are shared by IPWs between multiple node-pairs; and 4) are in close proximity to emergency response facilities. This dynamic prioritization mechanism holistically integrates the network characteristics and individual bridge properties in resilience-based decision for the road network.

Figure 5. Pareto Frontier of Optimal Solutions

Figure 6. Comparison of Network Resilience before and after Retrofit (Solution III)


Table 4. Details of Four Optimal Solutions in Pareto Frontier

<table>
<thead>
<tr>
<th>Solution ID</th>
<th>Cost</th>
<th>Mean Resilience</th>
<th>Number of bridges selected for retrofit</th>
<th>Bridges Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>25</td>
<td>0.76</td>
<td>7</td>
<td>5, 17, 8, 32, 10, 4, 33</td>
</tr>
<tr>
<td>II</td>
<td>62</td>
<td>1.07</td>
<td>14</td>
<td>22, 5, 28, 17, 20, 14, 12, 19, 27, 15, 24, 16, 36, 21, 37, 31</td>
</tr>
<tr>
<td>III</td>
<td>86</td>
<td>1.24</td>
<td>22</td>
<td>27, 11, 19, 16, 10, 31, 5, 17, 18, 37, 23, 30, 28, 14, 12, 24, 21, 22, 29, 36, 15, 20</td>
</tr>
<tr>
<td>IV</td>
<td>107</td>
<td>1.51</td>
<td>27</td>
<td>7, 6, 11, 19, 27, 31, 1, 5, 17, 8, 18, 37, 25, 26, 23, 30, 28, 14, 2, 24, 21, 35, 22, 29, 36, 20, 13</td>
</tr>
</tbody>
</table>

6.3 Improving network resilience by changing network topology through new construction

Opportunities may exist in a developing community to improve the resilience of the existing transportation network by altering its topology through new construction. For example, the hypothetical road network considered herein has two obvious areas of potential weakness as far as resilience is concerned. The first weakness is the branch from node 19 to node 28, highlighted with thickened lines in Figure 7, where four bridges - 26, 30, 36, and 37- are connected in series to the rest of the network through node 19. If any of the four bridges fail due to the earthquake, the area to the east of that bridge will be isolated from the rest of the community because an alternative path does not exist. The second weakness is if both bridges 18 and 19 fail, the entire community road system will be divided into two unconnected subsystems, and the resilience of the road system will instantly drop to 0.39. Relieving the burden on these two bridges by creating bypasses will increase the overall resilience of the network.

Suppose that as part of community development, Links S1-S5, shown by dashed lines on Figure 7, are possible candidates for construction to mitigate the above-mentioned potential risks. Suppose, further, that resources are available to construct only two additional roads out of the five candidates: one road to be selected from S1, S2, or S3 is to increase the connectivity of the branch from node 19 to node 28, and one road to be selected from S4 or S5 to relieve the burden on roads 18 and 19. The decision method outlined in Section 5 is applied to select alternatives that will most enhance the overall resilience of the road network. Table 5 lists the mean and percentage increase of the network resilience for each combination of possible selections. While all possible solutions improve the overall network resilience significantly, the combination of S2+S4 is most effective, with a 72.3% increase in network resilience from 0.61 to 1.05.
Figure 7. Hypothetical Bridge Network with Candidates for New Construction

Table 5. Impact of New Construction on Network Resilience

<table>
<thead>
<tr>
<th>Possible combinations</th>
<th>Mean of resilience</th>
<th>Percentage of increase in resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1+ S4</td>
<td>1.03</td>
<td>68.8%</td>
</tr>
<tr>
<td>S1+ S5</td>
<td>0.88</td>
<td>44.3%</td>
</tr>
<tr>
<td>S2+ S4</td>
<td>1.05</td>
<td>72.3%</td>
</tr>
<tr>
<td>S2+ S5</td>
<td>0.89</td>
<td>45.9%</td>
</tr>
<tr>
<td>S3+ S4</td>
<td>1.01</td>
<td>65.6%</td>
</tr>
<tr>
<td>S3+ S5</td>
<td>0.85</td>
<td>39.3%</td>
</tr>
</tbody>
</table>


7. Conclusion

This study has introduced a quantitative metric based on graph theory to measure resilience of a road/bridge network which permits risk mitigation alternatives for improving the resilience of transportation system to be evaluated and compared on a common basis. The method systematically integrates the network topology, redundancy level, traffic patterns, location of community emergency response facilities as well as failure probability of individual bridges, into the resilience indicator. Resilience analysis suggests that network resilience can be improved by increasing reliabilities of critical bridges through appropriate retrofitting, optimizing network topology through new construction, by altering traffic flow patterns through appropriate routing policies, and by strategically allocating emergency response facilities. However, the role that the transportation system plays before, during and after a disaster will be unique for each community. Stakeholders of communities of different sizes, populations and social-economic vulnerabilities and support systems are likely to reveal different values and preferences in evaluating resilience of their transportation systems. The resilience indicator proposed in this study provides a transparent framework for incorporating other attributes in addition to those discussed herein by adjusting the weights in the network resilience quantification. The proposed decision framework for effective risk mitigation through bridge retrofiting or new construction is formulated as a multi-objective optimization problem, which allows tradeoffs to be made between competing resilience and cost objectives and the subjective preferences of a decision maker to be factored in decision process.

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8. Reference


