QUANTIFYING THE SEISMIC RESILIENCE OF HIGHWAY NETWORKS USING A LOSS-ESTIMATION TOOL

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Abstract

Today *life-safety* is no longer the sole requirement of a highway system subject to a major earthquake. *Resilience* has been added to the list of requirements to ensure rapid recovery and minimal impact on the socio-economic fabric of modern society. In qualitative terms, a resilient system recovers quickly, whereas a non-resilient system does not. It is more difficult to express resilience in quantitative terms, yet it is important to try to do so. If resilience can be quantified, we can understand why some systems are more resilient than others. In this paper REDARS, a loss-estimation tool for highway systems, is used to identify factors affecting resilience and, by way of a demonstration application, show that column retrofitting and modest improvements in mobilization rates, can improve resilience by factor of 4 for a small-moderate sized city.

Introduction

Earthquakes remain one of the world's major problems. They occur frequently, without warning, and result in high death tolls, thousands of injuries, and crippling economic losses.

For many years earthquake engineering research around the world has focused on saving lives and minimizing the number of injuries, but, we now recognize that the protection of human lives is a necessary but not sufficient goal to minimize the social and economic impacts of a major earthquake. Recent data from U.S. natural disasters show that, despite the advances in earthquake engineering and other natural hazards, economic losses due to these disasters are escalating at an alarming rate, particularly over the last 25 years in the U.S.

The time has come to focus on controlling the economic and social losses from future earthquakes, in addition to life-safety, to prevent a socioeconomic catastrophe. It is the hypothesis of this paper (and others in this field) that these losses can be greatly reduced by building resilience into our infrastructure systems, and in this paper we explore the application of this concept to highway systems.

Resilience

Technically, *resilience* is the ability of a body to bounce back and recover its original shape after being subjected to stress. In societal systems, resilience is the ability of these systems to recover rapidly from a shock or disturbance. Fig. 1 shows schematically the effect of resilience on the response of a system, measured by the

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quality of service over time. In this figure an event occurs at time t_1 and there is an immediate loss of service from Q_0 to Q_1 (for example the number of passenger-miles traveled on a highway system) followed a period of recovery such that by time t_2, full service has been restored. Bruneau et al (2003, 2004) have used this framework to define loss of resilience, but in this paper we use Fig. 1 to quantify resilience and identify those factors that lead to resilient systems. If we are able to quantify resilience we are then be able to understand why some systems are more resilient than others. We would also be able to develop incentives for owners and decision makers to make infrastructure systems more resilient and measure progress towards developing resilience to natural disasters.

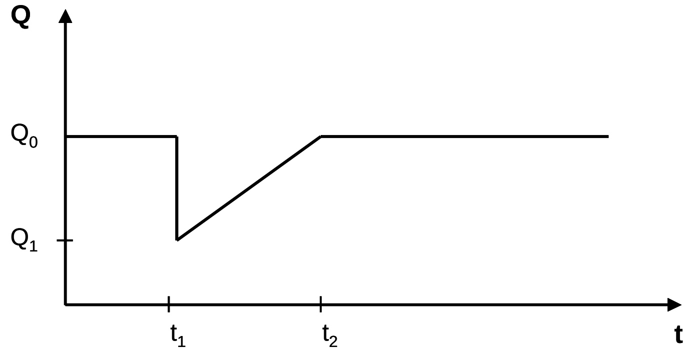


FIGURE 1. IMPACT OF AN EARTHQUAKE ON QUALITY OF SERVICE, Q (BRUNEAU ET.AL. 2003, 2004)

Quantifying Resilience

In Fig. 2 the initial impact of the event is the loss of service $\delta Q = Q_0 - Q_1$. This loss is the direct result of the vulnerability of the system to the event and the more fragile the system (the more vulnerable) the greater δQ. The rate of recovery (r) from Q_1 is assumed to be constant over time for the purpose of illustration, leading to a full recovery at time t_2. The recovery time (T) is a measure of the resilience of the system (Fig. 3); the smaller T, the higher the resilience; the higher T, the lower the resilience.

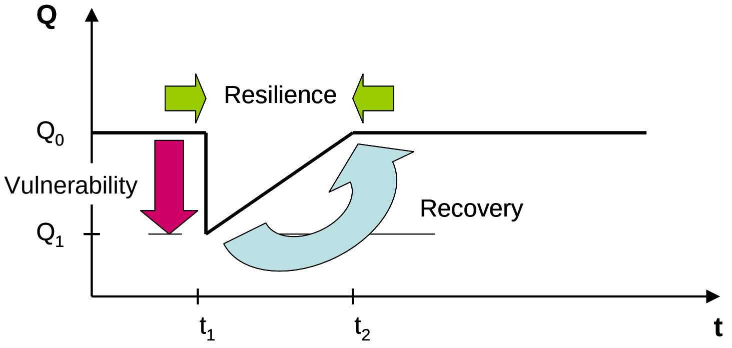


FIGURE 2. RESILIENCE AS A FUNCTION OF VULNERABILITY AND RATE OF RECOVERY (BUCKLE and LEE, 2006)

It follows that resilience is inversely proportional to recovery time T, and that

T is given by:

$$T = (t_2 - t_1) = \delta Q / r$$

Consequently, reducing vulnerability improves resilience. Likewise increasing the rate of recovery improves resilience, but doing both at the same time produces the most resilient systems.

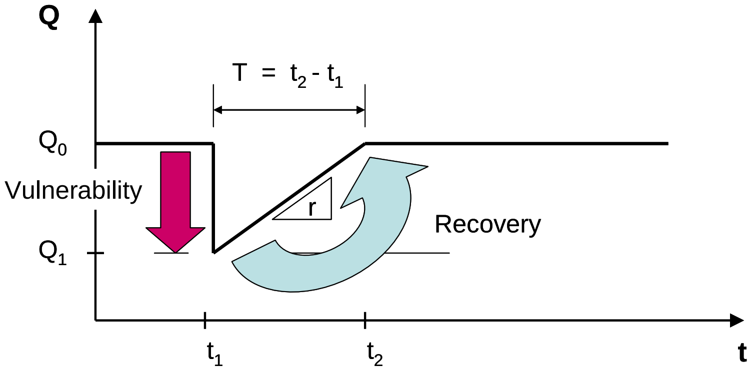


FIGURE 3. MEASURE OF RESILIENCE: TIME TO RECOVER TO PRE-EARTHQUAKE QUALITY OF SERVICE, T

As noted above, improving resilience can be achieved by reducing vulnerability and this may be done by building structural systems with capacity for extreme loads, retrofitting existing systems, adding redundancy, relocating co-located systems, reducing the interdependence of infrastructure systems, and avoiding the potential for cascading failures. However the cost of this mitigation (reducing vulnerability) can be prohibitive and an intelligent approach is necessary which balances expenditure of resources against likelihood of damage and the consequences of damage (impact on recovery time).

Also as noted above, resilience can be improved by increasing the rate of recovery and this can be achieved by empowering community response and resourcefulness, building emergency response capacity (not just at the local level but also regionally and nationally), anticipating needs and identifying resources ahead of time. New tools are now available for selected infrastructure systems that enable pre-event planning to be undertaken. These tools are based on system loss-estimation models and can be used to calculate system performance parameters (e.g. traffic flows) for either deterministic or probabilistic-based event scenarios. They therefore offer a methodology to estimate recovery times (e.g. T_{80}) and may therefore be used to quantify the resilience of such systems.

One such tool is REDARS (Werner et. al., 2000), which has been recently modified (REDARS 3) to allow the resilience of highway systems to be specifically studied (Werner et. al., 2013).

Resilient Highway Systems

The post-earthquake resilience of a highway system can be measured deterministically or probabilistically in the following ways, all of which are accommodated in REDARS 3:

- ***System-Wide Resilience*** -- is a single value of the time at which aggregated travel times or trip demands throughout the entire highway system achieve their pre-earthquake values.

- ***Location-Specific Resilience*** -- represents the time at which travel times and trip demands to/from any user-selected location achieves their pre-earthquake values. This enables the resilience to be assessed of travel to/from various locations that are vital to a region's emergency response and economic recovery, such as: (a) major medical centers; (b) airports and water ports; (c) government centers; (d) major centers of commerce; and (e) population centers.

- ***Route-Specific Resilience*** – represents the time at which travel times along any user-selected route within the highway system achieve their pre-earthquake values. This enables the resilience of travel to be assessed along various key routes within the system such as: (a) non-redundant and heavily traveled routes to/from centers of population or commerce; (b) lifeline routes that must accommodate emergency travel almost immediately after an earthquake; (c) routes for travel to/from emergency response facilities; and (d) major routes for interstate travel.

The resilience of a highway system can be affected by a variety of factors related to: (a) the highway system and surrounding region; (b) the reparability of the earthquake damage; and (c) post-earthquake traffic-management. These factors are discussed in the following sections.

System and Regional Factors

Factors related to the highway system and surrounding region that affect resilience, include:

- Size, redundancy, and traffic-carrying capacities of the highways and arterials
- Trip demands on the system and the resulting degree of pre-earthquake traffic congestion experienced by the system, and
- Proximity of centers of commerce and population to the earthquake damage.

Damage and Repair Factors

Factors related to the extent of damage to the system and the rate at which this damage is repaired, that affect resilience, include:

(a) Earthquake-induced Damage

The following factors affect the potential for earthquake damage to the components of a highway system (bridges, roadways, approach fills, tunnels, embankments, etc.) which, in turn, affect post-earthquake downtimes and system resilience.

- ***Seismic Risk Reduction Measures***. Whether or not seismic risk reduction measures have been implemented affects the potential for earthquake damage to the system components. Such measures include seismic design/retrofit of bridge structures, and soil improvement measures along the system's roadways, bridges, slopes, and embankments.

- ***State of Maintenance.*** Whether or not the various components are well maintained affects their performance during an earthquake. If components have deteriorated due to weathering and other factors, their seismic performance will be adversely affected.

- ***Soil Conditions.*** Highway components located on potentially-liquefiable soils or along unstable slopes that could slip during ground shaking, are more prone to earthquake damage and disruption than will components located on competent soils and slopes.

- ***Geologic Hazards.*** The proximity of the highway system to active faults affects the geologic hazards to which the system is subjected during an earthquake. Any element of the system that happens to cross a shallow fault that undergoes surface rupture could be damaged by the resulting relative ground displacement. Also, the level of ground motion hazard to which the highway system is subjected depends on the distance of the system to active faults in the region.

(b) Component Attributes

Bridge attributes affecting seismic performance include material of construction, span-support conditions, skew angle, whether they have been seismically designed, and if not, whether they have been retrofitted. Tunnel attributes affecting seismic performance include the tunnel radius, material of construction, construction type (cut-and-cover vs. drilled), and whether they have been seismically designed. Approach fill attributes affecting seismic performance include extent of compaction and type of fill.

(c) Damage Repair

The rate at which highway system damage can be repaired strongly affects system resilience. The damage repair rate will depend on the following factors:

- ***Bridge Damage Accessibility.*** Bridge repairs are slowed, if a damaged bridge crosses a river or other waterway, or is in close proximity to other roadways or structures that limit access to the damage.

- ***Repair Resource Mobilization.*** The time needed to mobilize repair resources affects total downtimes. This mobilization time depends on: (a) whether design of the repairs is needed; and (b) whether damage is widespread throughout the highway system and extends to other elements of the region's built infrastructure. If repair resources are scarce, mobilization times will be seriously affected. Stockpiling of emergency repair resources beforehand can reduce post-earthquake mobilization times.

- ***Geologic Hazards.*** Experience from past earthquakes has shown that earthquake-induced landslides can block highways, and that earthquake-induced failures of slopes or embankments can damage nearby highway components. In addition, earthquake-induced liquefaction of soils that support a bridge can severely damage both the foundations and substructure. Each of these geologic-hazard-related sources of highway damage can lead to extensive repair downtimes which slow recovery and decrease the resilience of the system.

- ***Accelerated Repairs.*** Accelerated repairs of key elements of a highway system can substantially reduce downtimes and improve resilience. An accelerated program for the repair of severely damaged freeways in Los Angeles after the Northridge Earthquake was particularly successful. It greatly reduced the downtime for affected sections of the freeway and reduced regional indirect losses due to the freeway damage. Network resilience was markedly improved.

Traffic Management Strategies

Traffic-management strategies can improve the resilience of a highway system. Such strategies can include:

- ***One-Way Traffic Strategies.*** Changing traffic flow directions from two-way to one-way on roadways near the system damage.

- ***Increased Traffic Capacities.*** Removal of parking lanes along major roadways near the damage can improve traffic flows and increase the recovery times in the vicinity of the damage.

- ***Staggering of Traffic Demands.*** The staggering of work hours among major employers in a region with severe highway damage can spread traffic demands over time and improve traffic mobility while the damage is being repaired. This will reduce congestion and improve repair times leading to faster recovery of the highway system.

Demonstration Application

This section presents a demonstration application of the REDARS 3 software to the quantification of seismic resilience of the highway system in Shelby County, Tennessee. This application consists of a deterministic analysis of system resilience after an earthquake of M_w 7.7 that simulates a repeat of the 1811-1812 New Madrid, Missouri events. These earthquakes caused strong shaking throughout the Midwest and were felt over much of the eastern United States. The analysis includes the response of bridges to ground motions, but does not include the effects of other hazards (liquefaction, landslide, etc.) nor does it include response of roadways and other highway components to this shaking. Ground motions from this earthquake are estimated using ShakeMap procedures (Wald et al., 2006).

Shelby County is located in the southwest corner of Tennessee, just north of the border between Tennessee and Mississippi. It includes the city of Memphis which had a population of over 655,000 in 2010. The Shelby County highway system is shown in Fig. 4. It includes a beltway of interstate highways that surrounds Memphis, major crossings of the Mississippi River along Interstates 40 and 55, and various arterials roadways. The system includes 466 bridges, of which 137 were constructed during or after 1990 and therefore are assumed to have been seismically designed, and 84 bridges that have been seismically retrofitted. The remaining 245 bridges have neither been seismically designed nor retrofitted.

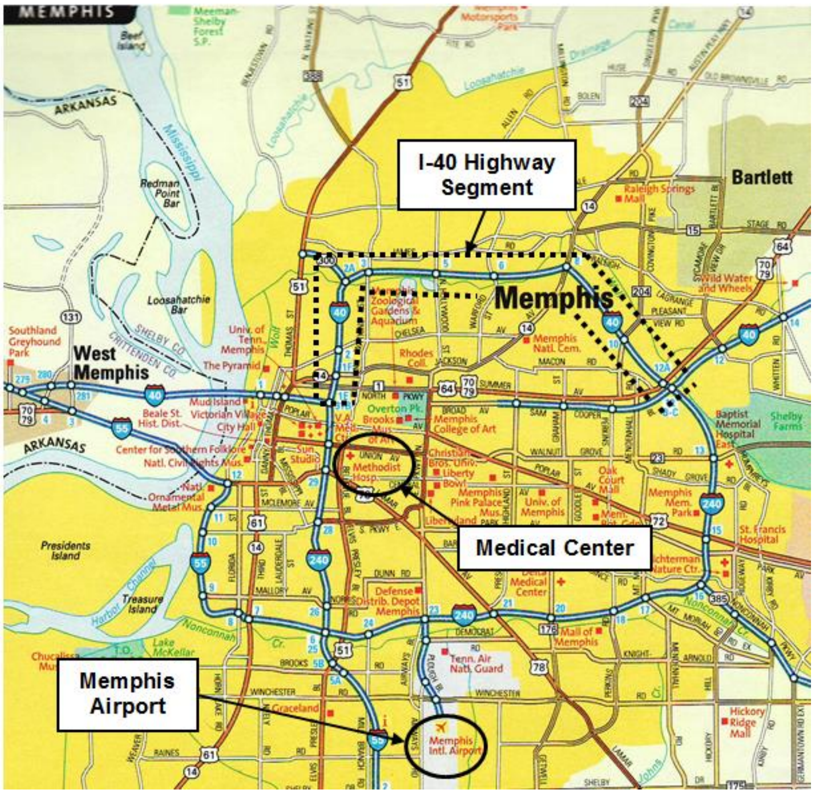


FIGURE 4. SHELBY COUNTY, TN, HIGHWAY SYSTEM SHOWING LOCATIONS AND ROUTE SEGMENT FOR RESILIENCE STUDIES

Analysis Procedure

The REDARS-3 methodology estimates (a) earthquake damage states for every bridge in the Shelby County highway system for the given ground motion, and (b) the cost and downtime for repair of each damaged bridge. These downtimes form system states at various post-earthquake times, i.e. network links that are closed due to bridge damage at various post-earthquake times.

Link closures will require drivers to detour around the damaged bridges and use alternative routes. This will cause traffic congestion that can be severe if many links throughout the system are closed at a given time. REDARS applies a transportation network analysis procedure to each system state, in order to estimate the extent of this congestion and how it affects travel throughout the highway system. The end results of the analysis for each post-earthquake system state represents the effects of this congestion in two ways: (a) travel times will be increased - i.e., it will take longer for travelers to get from their origin to their destination; and (b) trip demands on the system will be reduced - there will be a reduced propensity to travel because of the congestion. (i.e., trip demands on the system will be reduced).

The final phase of the analysis uses these increased travel times and reduced trip demands to determine system resilience.

As noted previously, resilience will strongly depend on the estimated downtimes of the damaged bridges while they are being repaired. Downtimes are estimated by a model that has been developed for bridges in the Central and Southeastern United States (CSEUS). The model uses component-based fragility functions which enable better estimates to be made of downtimes than previously possible. However, downtime estimates are uncertain, and these uncertainties should be kept in mind when reviewing the resilience results given in this paper. Default repair parameters developed by Werner et al. (2013) are used to estimate the downtimes in this application.

In addition to downtimes during repairs, additional time will be needed to mobilize repair resources at the sites of the damaged bridges before the repairs can proceed. Estimation of this mobilization time is uncertain, because it depends on factors that cannot be anticipated beforehand. For example, if existing repair resources in a region are insufficient to address damage to the entire built infrastructure in the region (in addition to the highway system), there may be competition for these resources until additional emergency resources arrive. The bridge repair model used in this application, invokes a mobilization time scale factor that depends on the earthquake magnitude, in order to roughly account for the effect of additional infrastructure damage on mobilization time. For the major earthquake (M_w=7.7) considered in this application, a mobilization time scale factor of 1.30 was used, and applied to the repair downtime of each bridge to obtain a total downtime for that bridge. Since the damage to the built infrastructure in the region due to such a large earthquake could be severe, a mobilization time scale factor of 1.30 does not seem unreasonable. It is noted that, for this earthquake magnitude, a value of 1.30 corresponds to the default value built into REDARS 3. This factor can be overridden by the user.

The major crossings of the Mississippi River by Interstates 40 and 55 are not included in this application because component-based fragility functions for these complex bridges have not yet been developed.

Analysis Results

To illustrate the usefulness of the REDARS software tool, the results of three cases are given below:

1. Resilience of the highway system in its current state for each of the resilience definitions described above (system-wide, location-specific, and route-specific). In the results presented below, this case is the 'Baseline Scenario'.

2. Improved resilience of the highway system if the remaining number of non-seismically designed bridges, that have not yet been retrofitted, were retrofitted with steel jackets (245 bridges). In the results presented below, this case is the 'Bridge Improvement Scenario'.

3. Improved resilience of the highway system if repair times were reduced by (a) reducing the mobilization time scale factor from 1.30 to 1.15, and (b) repair times were reduced by 20% over those used in the baseline case (No. 1 above). In the results presented below, this case is the 'Repair Efficiency Scenario'.

(a) Effect of Different Scenarios

Comparison of the resilience curves in Figs 5 to 8 show how various resilience definitions (i.e., system-wide, location-specific, and route-specific travel time and trip demand measures) are affected by the different scenarios. These figures show the following trends:

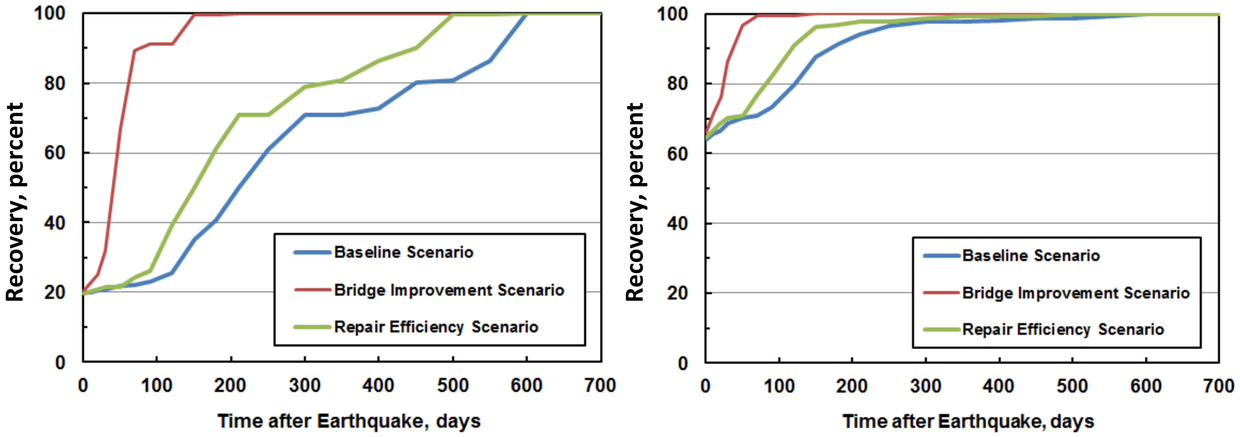
- For all resilience definitions, the repair-efficiency and bridge-improvement scenarios improve the resilience throughout the Shelby County region for both measures of resilience: travel time and trip demand.

- The bridge-improvement scenario leads to the largest improvement in resilience. This improvement is greatest for the route-specific resilience, for which the time to reach 100% of pre-earthquake performance is less than 150 days, as compared to over 600 days for the baseline scenario.

- The bridge-improvement and repair-efficiency scenarios improve the rate of recovery for the system-wide and location-specific travel-times at virtually all post-earthquake times.

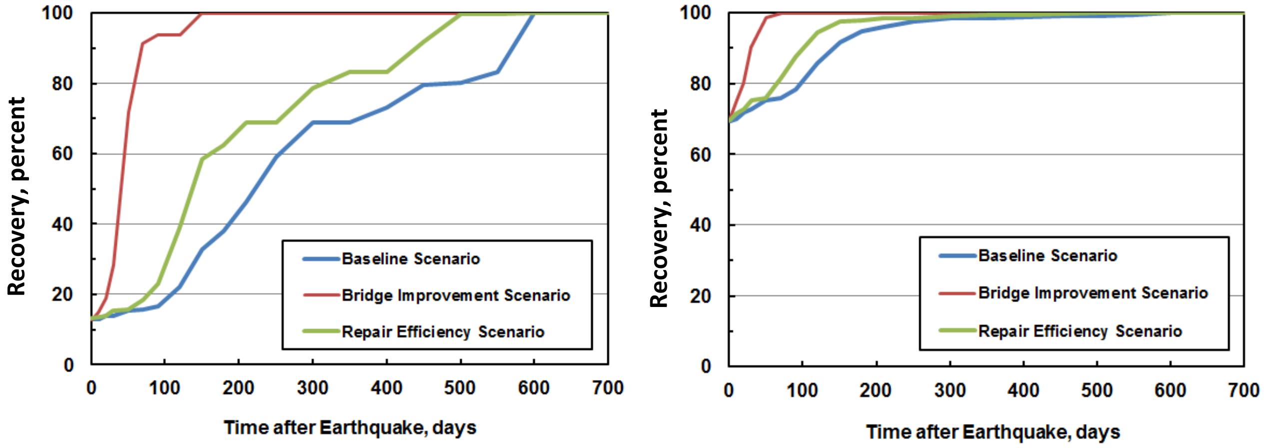
- The repair-efficiency scenario has little effect on the recovery of the I-40 route-specific travel-time until about 400 days or so after the earthquake. After this time, this scenario substantially improves the rate of recovery relative to the baseline scenario.

- For all scenarios (including the baseline scenario), the trip-demands recover much faster than the travel times. The bridge-improvement and repair-efficiency scenarios give additional improvements in these recovery rates.



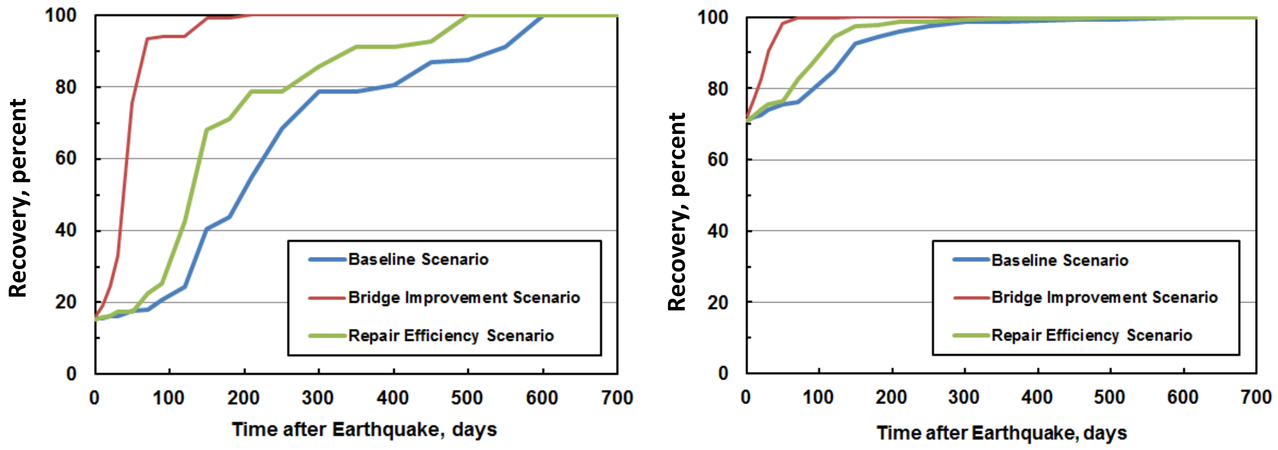
a) Travel Times **b) Trip Demands**

FIGURE 5. EFFECT OF VARIOUS SCENARIOS ON RESILIENCE OF SYSTEM-WIDE TRAVEL



a) Travel Times **b) Trip Demands**

FIGURE 6. EFFECT OF VARIOUS SCENARIOS ON RESILIENCE OF LOCATION-SPECIFIC TRAVEL (TO/FROM MEDICAL CENTER)



a) Travel Times **b) Trip Demands**

FIGURE 7. EFFECT OF VARIOUS SCENARIOS ON RESILIENCE OF LOCATION-SPECIFIC TRAVEL (TO/FROM MEMPHIS AIRPORT)

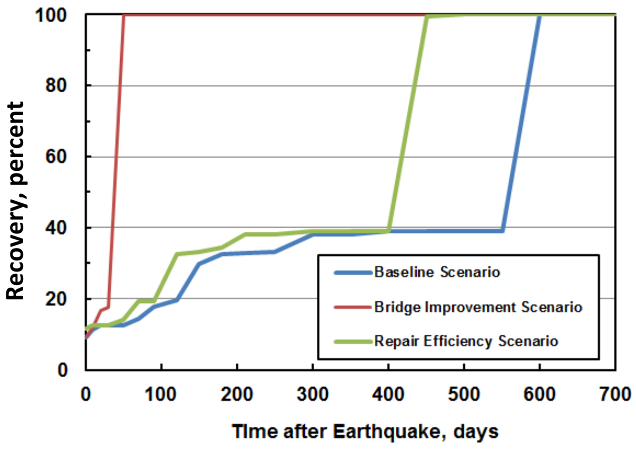


FIGURE 8. EFFECT OF VARIOUS SCENARIOS ON RESILIENCE OF ROUTE-SPECIFIC TRAVEL TIMES (I-40 SEGMENT)

(b) <u>Effect of Different Resilience Definitions</u>

Computed system-wide, location-specific, and route-specific travel-time resiliencies for each scenario are compared in Figs 9 to 11. These figures show that:

- The different resilience definitions can produce very different resilience values. These different values strongly depend on whether the baseline, location-specific, or route-specific scenarios are being applied.

- The travel times to/from the Memphis Airport are slightly more resilient than the system-wide travel times, and are also slightly more resilient than the Medical Center travel times. The recovery of the system-wide travel times and the Medical Center travel times are nearly identical.

- Comparison of route-specific and system-wide travel-time recovery times are scenario-dependent. These different rates of recovery are similar to the bridge-improvement scenario. Under the baseline and repair-efficiency scenarios, the recovery of the system-wide travel time typically exceeds that of the route-specific travel-time.

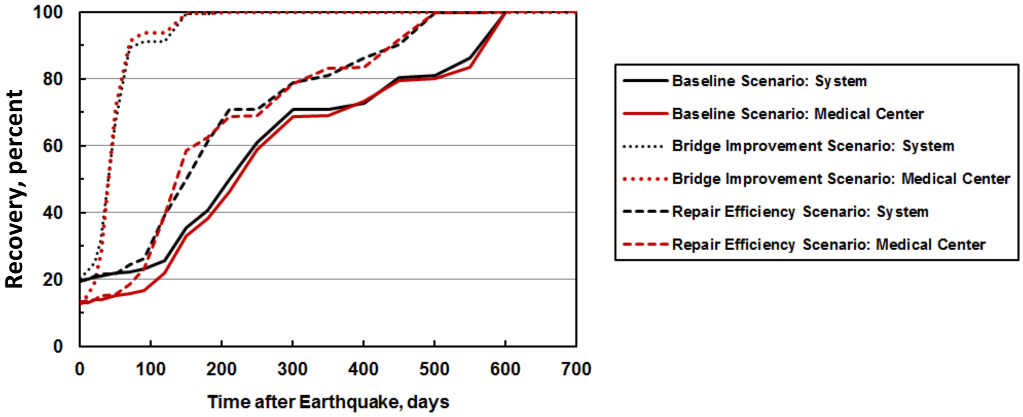


FIGURE 9. COMPARISON OF TRAVEL TIME RECOVERY: SYSTEM-WIDE AND LOCATION-SPECIFIC (MEDICAL CENTER)

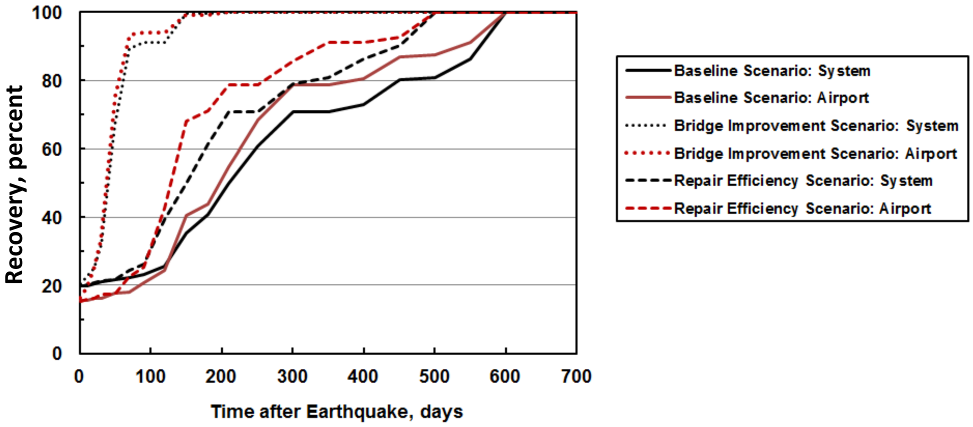


FIGURE 10. COMPARISON OF TRAVEL TIME RECOVERY: SYSTEM-WIDE AND LOCATION- SPECIFIC (MEMPHIS AIRPORT)

Figure 12 compares recovery rates based on trip-demand for the entire system and the Medical Center. The figure shows that like the recovery in travel-time, trip-demand recovery is scenario dependent. For the baseline scenario and the repair-efficiency scenario, the trip demands to/from the Medical Center are slightly more resilient than the system-wide trip demands. However, when the bridge improvement scenario is in place, the resilience of the trip demands for the Medical Center is very high. Similar results were found for the Memphis Airport location.

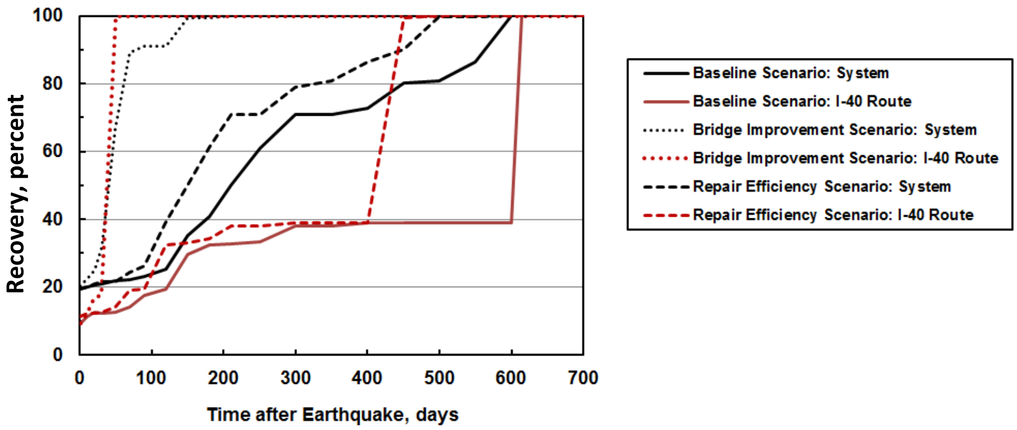


FIGURE 11. COMPARISON OF TRAVEL TIME RECOVERY: SYSTEM-WIDE VS. ROUTE SPECIFIC (I-40 ROUTE)

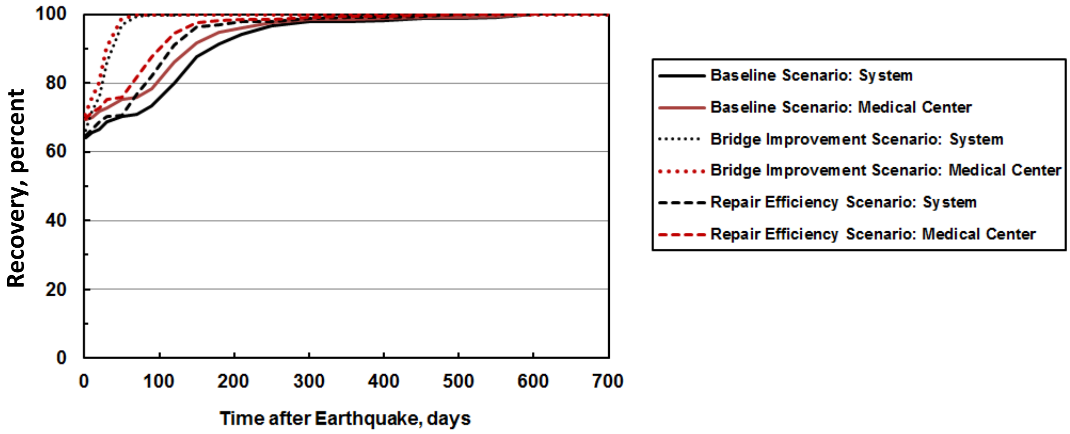


FIGURE 12. COMPARISON OF TRIP DEMAND RECOVERY: SYSTEM-WIDE VS. LOCATION-SPECIFIC (MEDICAL CENTER)

Conclusions

Today *life-safety* is no longer the sole requirement of a highway system subject to a major earthquake. *Resilience* has been added to the list of requirements to ensure rapid recovery and minimal impact on the socio-economic fabric of modern society. In qualitative terms, a resilient system recovers quickly, whereas a non-resilient system does not. It is more difficult to express resilience in quantitative terms than qualitative ones, yet it is important to try to do so. If resilience can be quantified, we can understand why some systems are more resilient than others.

It is shown that factors affecting resilience include: system and regional factors, damage and repair factors, and traffic management strategies. Furthermore it is helpful to distinguish between system-wide resilience, location-specific resilience, and route-specific resilience.

From the results of a demonstration application, it may also be concluded that REDARS, a loss-estimation methodology for highway systems, is also a useful tool for quantifying resilience. For example, it has been shown that column retrofitting and modest improvements in the mobilization rates, can improve resilience for a small-to-moderate sized city by factor of four.

Acknowledgments

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