



SEISMIC RISK ASSESMENT OF RETROFITTED TRANSPORTATION SYSTEMS

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SUMMARY

This paper discusses a methodology to evaluate the seismic performance of highway transportation networks considering bridge retrofit status. The methodology focuses on the seismic risk analysis of the highway transportation network, in which the bridge fragility information (with and without retrofit) is integrated into the transportation network model, and system performance, as measured by drivers' delay, is obtained through the traffic assignment in the intact and damaged network. System performance of the highway network in the Los Angeles area is evaluated for five retrofit status conditions (0%, 22%, 50%, 75% and 100% of all the bridges retrofitted), including development of system risk curves, expressed as probability of exceedance versus drivers' delay. The system simulation shows that retrofitted bridges will not only experience less severe physical damage, but also produce improvements in system performance by decreasing drivers' delay. A preliminary cost benefit analysis is then carried out to compare the cost effectiveness of the retrofit strategies. The benefits resulting from the retrofit measures consist of avoided loss due to reduced drivers' delay and reduced repair costs for damaged bridges, which are estimated in addition to the retrofit cost. The analysis demonstrates that avoided annual loss due to reduced drivers' delay contributes much more to the annual benefit than the reduced repair cost, and that all of the non-zero retrofit strategies are cost-effective with almost the same ratio (as large as 3.0) of annual benefit to annual cost.

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INTRODUCTION

Transportation systems, including highways, railroads, airports and harbors, are critical components of society's infrastructure systems. They are needed for the welfare of the general public, specifically for commercial, industrial and cultural activities on a national as well as international scale, and to facilitate transportation of search and rescue and medical teams, the injured to hospitals, repair and restoration crews and materials, and daily supplies for citizens following disasters. In this respect, under a natural or manmade disaster (e.g., earthquake, flood, etc.), it is critically important that the transportation system remains operational or that its function be repaired or restored as quickly as possible. Past experience has shown too often that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can severely disrupt traffic flow, thus negatively impacting the economy of a region as well as post-earthquake emergency response and recovery activities. Furthermore, the extent of these impacts will depend not only on the nature and magnitude of the seismic damage sustained by the individual components, but also on the mode of functional impairment of the highway system as a network resulting from physical damage to its components. In order to estimate the effect of the earthquake on the system performance of the transportation network, an analytical framework was developed to integrate bridge and other structural performance models with a transportation network model in the context of seismic risk assessment (Shinozuka [5]). The effect of retrofitted bridges on system performance and the effect of post-event repair effort were further investigated by Shinozuka [6].

The seismic performance of bridges, the most seismically vulnerable components in the highway transportation network, is probabilistically described by fragility curves, and can be significantly enhanced by various retrofit measures, such as steel jacketing (Shinozuka [7]). When subject to future earthquake events, the retrofitted bridges will not only experience less severe physical damage but will also result in significant improvement of the system performance by decreasing drivers' delay, a comprehensive index of system performance (Shinozuka [6]). It can be conceived that when more bridges are retrofitted in a highway network, repair costs for damaged bridges will be lower, and less loss due to the drivers' delay will be suffered. On the other hand, more money would be paid for the retrofit effort. In order to evaluate various retrofit strategies, a complete cost-benefit analysis should be performed to consider the bridge retrofit cost, repair cost and losses due to drivers' delay.

The purpose of this research, however, is to investigate the effect of varying bridge retrofit status for an example highway transportation system, and to perform a preliminary cost-benefit analysis to evaluate the cost effectiveness of the varying levels of retrofit. First, the methodology for the seismic risk analysis of transportation systems is introduced. Then, the drivers' delay under five cases of retrofit status, 0%, 22%, 50%, 75% and 100%, are evaluated and a system risk curve is developed for each case. Finally, a preliminary cost benefit analysis is carried out, based on estimated repair costs, retrofit costs and losses due to drivers' delay.

METHODOLOGY

Highway System: Assessing Structural Component and Network Damage

Highway transportation systems are comprised of numerous structural components, located in equally complex natural and built environments. Among the engineered components, bridges are the most vulnerable structural components under earthquake conditions. Thus, bridges are the only structures considered to be seismically vulnerable in this analysis. For the purpose of simulation, every bridge in the study region is considered an independent structure and determination of the degree of damage to each bridge can be treated as an independent statistical experiment.

In this study, the fragility curves for bridges with and without retrofit (Figure 1) are taken from Shinozuka [6], following the traditional form of a lognormal distribution described by two parameters; the median value, C , and the log standard deviation, ζ . The fragility curve for retrofitted bridges shows a 55%, 75%, 104%, and 143% improvement for minor, moderate, major and collapse damage states, respectively (Shinozuka [7]).

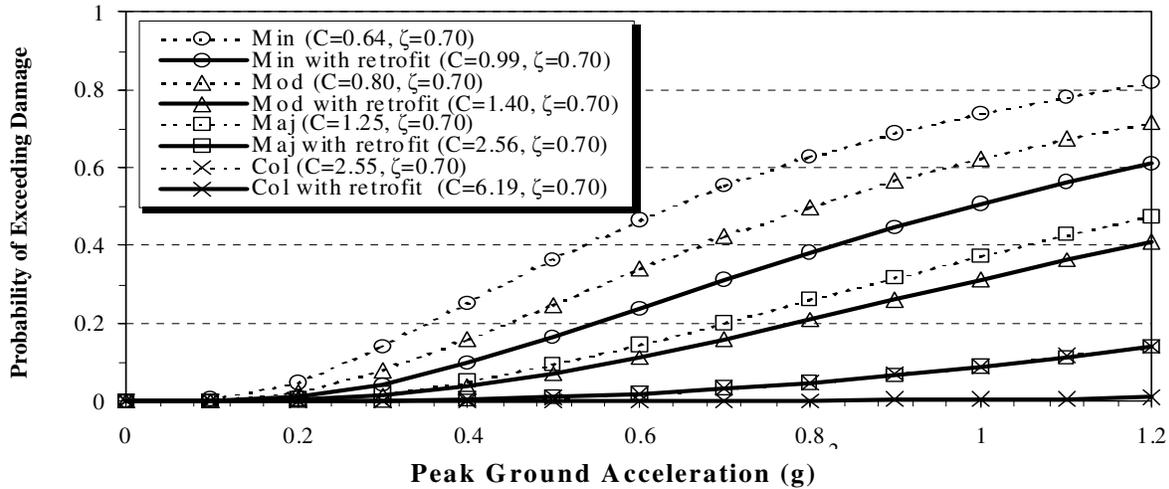


Figure 1: Fragility Curve for Bridges With and Without Retrofit

These fragility curves are utilized to generate, using Monte Carlo simulation, the state of damage for each and every Caltrans’ bridge in Los Angeles and Orange Counties under the postulated scenario earthquakes. Therefore, the following analysis applies only to the bridge population as it existed prior to any post-Northridge retrofit.

Table 1: Change in Road Capacity and Free Flow Speed

State of Link Damage	Capacity Change Rate	Free Flow Speed Change Rate
No Damage	100%	100%
Minor Damage	100%	75%
Moderate Damage	75%	50%
Major Damage	50%	50%
Collapse	50%*	50%*

* Local Detour Route Considered

Following the 1994 Northridge earthquake, the highway transportation system in the Los Angeles metropolitan area demonstrated a degree of system resiliency that was activated by enlisting and integrating some seismically unaffected secondary highways and artillery streets into the expressway network after it had suffered from the loss of several bridges. For this reason, in this analysis, alternate routes are considered to exist, although they have less traffic capabilities in terms of both free flow speed and capacity compared with the segment or the link of the expressway they replaced. This study quantifies the changes in these capacities as shown in Table 1, in terms of percent relative to the values under intact conditions, depending on the degree of the link damage. Link damage is represented by the worst state of damage of the bridges on that link (this is a bottle-neck hypothesis; if, for example, one of

the bridges on a link suffers from major damage, and if that is the worst state of damage, the link is assumed to have major damage.). These percentage values also account for the changes resulting from the repair work. The values in Table 1 are hypothetical and future research is needed to develop more reliable values.

Calculating a Comprehensive System Performance Index: Drivers' Delay

In order to define the network performance as a whole after an earthquake, a comprehensive index of performance is introduced. Following the method documented by Shinozuka [5], the index used here is the "Drivers' Delay". This is defined as the increase in total daily travel time for all travelers, including commuters and commercial vehicles, caused by earthquake induced delays. Essentially, it is the difference between the total daily travel time for all network travelers on the damaged network and that on the original undamaged network.

$$TT = \sum_a x_a t_a(x_a) \quad (1)$$

$$Delay = \sum_a x'_a t'_a(x'_a) - \sum_a x_a t_a(x_a) \quad (2)$$

Equation 1 delineates the calculation of the total daily travel time for all network users, in hours per day; where x_a is the flow on link a (in Passenger Car Unit per day), and t_a is the travel time on link a (in hours per Passenger Car Unit). Thus, the product of the two yields the total daily travel time for all network travelers on link a . The summation over all the links yields the total daily travel time on the entire network. Equation 2 describes the calculation of Drivers' Delay. The notation in Equation 2 is the same as in Equation 1 with the exception that the primed variables denote the case of the damaged network, and the unprimed variables refer to the original undamaged network. Note that "Drivers' Delay", when calculated this way, has units of hours per day. In order to get a total "Drivers' Delay" with unit of hours, this expression must be integrated over all the days that a delay persists.

The travel time on a link is calculated by utilizing a link performance function developed by the United States Bureau of Public Roads:

$$t_a = t_a^0 \left[1 + \alpha \left(\frac{x_a}{C_a} \right)^\beta \right] \quad (3)$$

where t_a^0 is the travel time at zero flow on the link a (this is simply the link's length divided by the speed limit); C_a is the "practical capacity" of the link, and α and β are variable parameters. Ordinarily, and in this study, $\alpha = 0.15$ and $\beta = 4.0$. It is important to note that this empirically derived expression asserts that the travel time on a link carrying 100% of capacity is 15% greater than the free flow time.

Determining the flow on each link depends on the availability of origin-destination (OD) data. Given the difficulty of collecting such a set of traffic flow data over a regional dimension, the OD data are developed only occasionally over the years and hence lags behind the change in traffic patterns. For this and other reasons, the data represent the traffic flow characteristics approximately. In this context, we developed a method by which a large size OD matrix was reduced to a manageable size following Shiraki [4]. This method relies upon the Thiessen function (in ArcGIS software [1]) which reduces the number of OD locations to the number of the nodes of the freeway network, each representing OD information within the Thiessen polygon developed around that node. This significantly reduces the matrix dimension

and makes the OD matrix usable in the PC-based near real-time traffic flow simulation. Upon producing such a useable origin-destination matrix, the flow between links must be solved using an equilibrium analysis.

Using the methods discussed here, it is possible to develop a rudimentary measure of a system's performance as a network given any state of damage to its components (bridges).

Developing a Risk Measure

Given the possibility of performing multiple simulations for a study region, measures of risk for the spatially distributed highway system can be developed using the methods introduced in Chang [2]. Utilizing a number of earthquake scenarios, and calculating their probabilities of exceedance, risk curves can be produced for the system in question. A risk curve is a plot of the probability of exceeding a certain hazard level versus a measure of damage or loss (in this case, Drivers' Delay). A set of these curves is produced in the case study discussed later in this paper. The spatial distribution of peak ground acceleration (PGA) for the selected scenario events was modeled using the USC-EPEDAT (Early Post Earthquake Damage Assessment Tool) software, jointly developed by the University of Southern California and EQE International, adapting the original EPEDAT software (Eguchi [3]).



Figure 2: Highway Network in Los Angeles and Orange Counties

SYSTEM PERFORMANCE UNDER DIFFERENT RETROFIT STATUS

Network Model

Figure 2 displays the freeway and state highway network considered in this study. The study is limited to the freeway network in Los Angeles and Orange Counties, in the Los Angeles Metropolitan Area. This network model consists of 148 nodes and 231 links. The total number of bridges in this network is 3147.

The network is defined in terms of nodes and links, where nodes consist of locations where two or more highway intersect (usually interchanges), as well as locations where a highway crosses the boundary of the study area. A link is defined as a line (not self-intersecting) between two nodes with no other nodes in between. The link characteristics are described by free flow speed and flow capacity. The free flow speed for a link is based upon its speed limit, which is assumed to be 65 miles per hour on freeways, and 35 miles per hour on highways. This is done for analytical simplicity, and can be adjusted for regional differences. Similarly, the practical capacities for freeway and highway links are assumed to be 2500 and 1000 passenger car units per hour, respectively.

The origin-destination data used in this paper consists of 1997 southern California origin-destination survey results for 3217 traffic analysis zone. The reader is referred to a report by the Southern California Association of Governments [9] for the details. As mentioned in the previous section, Thiessen polygons are utilized to convert the 1997 SCAG survey data to node OD data for the freeway network shown in Figure 2.

Traffic Analysis

To perform the traffic equilibrium analysis numerically, the method of user optimizing deterministic assignment is used with the aid of the incremental assignment technique. A speed ratio η for each link, representing one measure of system performance degradation, is defined as:

$$\eta_a = \frac{S'_a}{S_a} \quad (4)$$

where, η_a is the speed ratio on link a , S_a is the flow speed on link a under intact conditions, and S'_a is the flow speed on link a under damaged conditions. S'_a thus obtained is then input into Equations 1, 2 and 3 for the calculation of the total travel time in the damaged network system.

Retrofit Cases

To compare the system performance of the retrofitted system at different levels of retrofit, five retrofit cases are considered: 1) 0% of bridges retrofitted (no retrofit); 2) 22%; 3) 50%; 4) 75% and 5) 100%. Case 2 corresponds approximately to the current retrofit status of Caltrans' bridges in Los Angeles and Orange Counties (700 out of 3147 retrofitted). In Cases 2, 3, and 4, the retrofitted bridges are randomly selected from all bridges by simulation, and 10 sub-cases (samples of bridges retrofitted) of each case are generated. The damage state of each bridge is then simulated based on its site peak ground acceleration and fragility curve, considering whether it is retrofitted or not.

System Performance: Drivers' Delay

Table 2 shows daily drivers' delay (for Cases 2, 3 and 4, this is the average value over the 10 sub-cases) for the freeway network subjected to two earthquake scenarios. The total travel time per day under intact conditions is 9.23×10^5 hours. Due to the difference in the magnitude and PGA spatial distribution between the two scenarios, the drivers' delay resulting from the two scenarios are different, but demonstrate the same trend; the drivers' delay decreases as the percentage of retrofit increases. However, this curve is not linear as shown in Figure 3, which demonstrates the nonlinear dependence of system performance of the network on its components. Figure 4 gives the system risk curves under different cases of retrofit status for the 47 scenario earthquakes (Chang [2]) used to approximately represent the regional seismic hazard, wherein the system risk (drivers' delay) becomes steadily smaller as higher percentage of bridges are retrofitted.

Table 2 Average Daily Drivers' Delay

Scenarios	Daily Drivers' Delay (*10 ⁵ Hours)				
	Case 1	Case 2	Case 3	Case 4	Case 5
Elysian Park M7.1	19.3	17.7	14.1	10.1	5.4
Malibu Coast M7.3	22.4	21.4	18.9	14.4	9.0

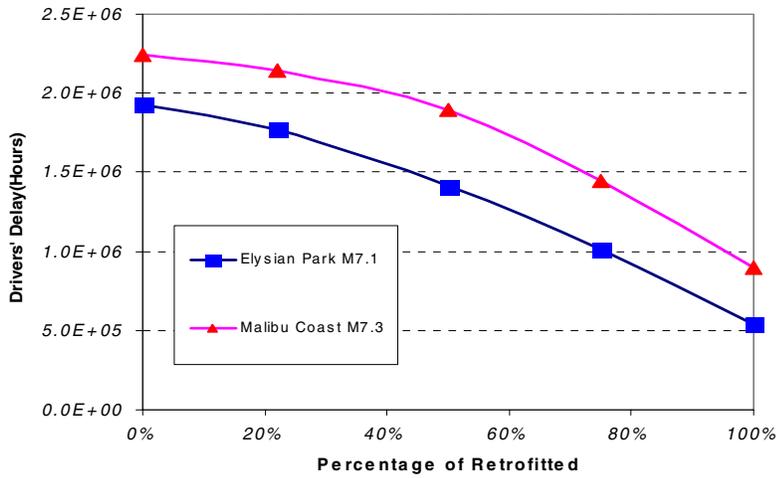


Figure 3 Comparison of Daily Drivers' Delay

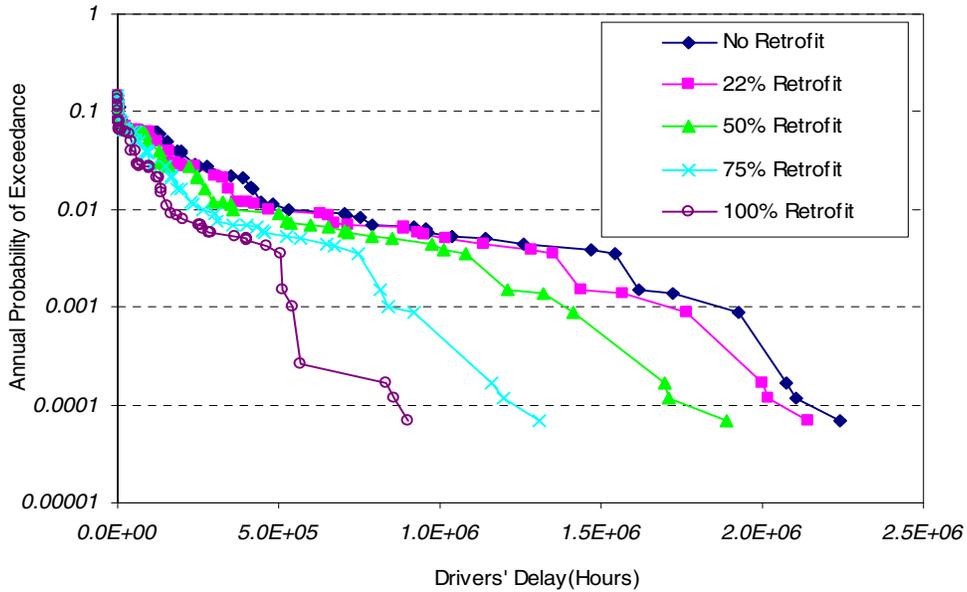


Figure 4 Risk Curves for Drivers' Delay for Different Retrofit Cases

COST- BENEFIT ANALYSIS

Loss Estimation

Retrofit costs increase as more bridges in the network are retrofitted, but less repair cost and loss from drivers' delay can be expected. Based on this, even with sufficient budget, it is not necessarily most cost effective to retrofit all the bridges in the network and in some cases, no retrofit may be better than complete retrofit. A cost-benefit analysis should be carried out to assess the various retrofit strategies.

There are three kinds of cost or losses addressed by the current cost-benefit analysis: bridge repair cost after an earthquake event, loss due to drivers' delay, and retrofit cost. The repair cost of damaged bridges is the direct economic loss. The loss due to drivers' delay is assumed to represent the indirect economic loss due to the dysfunction of the network in this preliminary economic analysis.

Loss due to drivers' delay: According to a TTI (Texas Transportation Institute) report [10], the average cost per hour's delay due to traffic congestion, including the cost of time and fuel, was around \$16.70 in 1997 in the United States. Although other costs may result from other negative effects of travel delays, it is reasonable to take this value as an initial and conservative estimate for the loss due to drivers' delay.

Repair cost: Bridge repair costs are assumed to be proportional to the bridge's replacement value, depending on its damage state. The replacement value is estimated to be the product of the deck area and a unit replacement value. Unit replacement values will vary depending on the bridge's structural type, material and other factors. Based on Caltrans' data, \$150/ft² is a reasonable estimate and is used uniformly for all the bridges at this stage of the analysis. The repair cost factors corresponding to different damage states are taken from the values recommended by HAZUS99-2 (NIBS [4]).

Retrofit cost: Depending on the retrofit measure and bridge type, the retrofit cost per unit deck area is variable, but has been assumed to be 20% of the replacement value of each bridge in this study.

Table 3 gives an estimate of these costs or losses, and avoided costs or losses when the highway network is subjected to a representative scenario earthquake (Elysian Park M7.1). The table clearly shows that as more bridges are retrofitted (higher percentage), more repair costs and daily losses due to drivers' delay are avoided. It should be noted that the daily loss due to drivers' delay is not the total loss due to drivers' delay, which should be calculated by considering the recovery curve for system performance over time.

**Table 3 Loss Resulted from Scenario Earthquake: Elysian Park M7.1
(in Million Dollars)**

Loss	Case				
	1	2	3	4	5
Daily Loss due to Drivers' Delay	32.1	29.4	23.5	15.4	9.0
Repair Cost	31.1	26.2	18.2	13.1	8.7
Avoided Daily Loss due to Drivers' Delay	0	2.7	8.6	16.7	23.1
Avoided Repair Cost	0	4.9	12.9	18.0	22.4

Cost Benefit Analysis

The benefit from retrofit is the sum of avoided loss due to drivers' delay and reduced repair cost for damaged bridges. If the ratio of the expected benefit to the expected cost (retrofit cost) is greater than 1,

the measure is considered to be cost effective. The expected annual benefits of retrofit measures can be expressed as

$$B_i = \sum_{i=1}^N (L(S_0 | Q_i) - L(S_R | Q_i)) \cdot p_i + \sum_{i=1}^N (L(D_0 | Q_i) - L(D_R | Q_i)) \cdot p_i \quad (5)$$

Where N = number of possible earthquakes;
 L = estimated loss;
 S_0 = system performance without retrofit;
 S_R = system performance with retrofit;
 D_0 = components' physical damage without retrofit;
 D_R = components' physical damage with retrofit;
 Q_i = i th possible earthquake;
 p_i = annual probability of i th possible earthquake.

By modifying the formula in Chang [2].

Table 4 Cost- Benefit Analysis (in Million Dollars)

Economic Index	Case				
	1	2	3	4	5
Annual Avoided Loss Due to Drivers' Delay (1)	0	2.55	5.71	9.9	12.74
Annual Reduced Repair Cost (2)	0	0.10	0.24	0.34	0.44
Annual Benefit (3)=(1)+(2)	0	2.65	5.95	10.24	13.18
Annual Retrofit Cost (4)	0	0.94	2.13	3.20	4.26
Cost Effectiveness (5)=(3)/(4)	/	2.83	2.8	3.2	3.09

The first term in Equation 5 in the context of this paper is the avoided loss due to drivers' delay. When the damaged bridges are gradually repaired, the system performance will improve accordingly with decreased daily drivers' delay (Shinozuka [2]) over time. It should be noted that drivers' delay won't persist forever. Once all the bridges are repaired, drivers' delay is reduced to zero. It can be conceived that the more destructive the earthquake, the longer the elapsed time required for system recovery. However, in this study, we assume the network can linearly recover its system functionality within 3 months (90 days) after any of the 47 scenario earthquakes, regardless of earthquake magnitude or destructiveness. Future research will be carried out to consider the system recovery curve after any event for a more refined estimate of total drivers' delay.

The second term is another benefit gained from retrofitted bridge components: reduced repair cost. The retrofitted bridges have enhanced fragility curves and will experience less severe physical damage, leading to lower expected repair costs in future earthquake events. The difference between the expected

repair cost before and after retrofit is the reduced repair cost. In each term in Equation (5), annual “hazard consistent” probabilities for the set of scenario earthquakes are considered to obtain the expected annual benefit.

The expected annual retrofit cost depends on the assumed retrofit status of the bridges and is estimated by evenly distributing the total retrofit cost over the period during which the retrofitted bridges demonstrate the enhanced seismic performance.

$$C_t = C_R / T \quad (6)$$

Where C_t = the expected annual cost (retrofit cost)

C_R = total retrofit cost (in current value)

T = the length of the analysis period (in year).

Table 4 shows the detailed cost-benefit analysis of the latter four retrofit cases with $T=50$ years. In each of Case 2, 3, 4 and 5, the avoided loss due to drivers’ delay dominates the annual benefit, while the reduced repair cost constitutes only a small fraction (less than 4%). The cost-benefit analysis also shows that the latter four retrofit strategies are cost effective with the cost-effectiveness factor (annual benefit/annual cost) as large as 3.0.

CONCLUSION AND DISCUSSION

This study first demonstrates the effectiveness of retrofitted bridges in improving transportation network system performance based on a methodology for the seismic risk analysis of transportation systems. Further, the preliminary cost benefit analysis for the highway network in the Los Angeles area shows that the retrofit measures are also cost effective in any of the four cases of retrofit status: 22%, 50%, 75% and 100% of bridges retrofitted. In these cases, the avoided loss due to drivers’ delay contributed much more to the total benefit obtained from the retrofit measures, compared with the reduced repair cost of damaged bridges. For a more reliable economic analysis, future study will focus on obtaining total drivers’ delay resulting from any specific scenario earthquakes by developing the system performance recovery curve, and refining models for estimating unit cost due to drivers’ delay, the bridge repair cost relative to the bridge’s structural type, damage state and location, and the retrofit cost related with the bridge type, age, retrofit measure and other factors.

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