# Seismic Performance of Transportation Networks

# 지진으로 인한 교통망 피해추정 기법

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### 국문요약

본 연구는 캘리포니아 내 고속도로망을 대상으로 지진발생 후 교통흐름의 변화를 평가하는 기법에 대하여 이루어졌으며, 고속도로망 상에 위치한 교량의 손상정도가 평가기법의 가장 기본적인 요소로 사용되었다. 본 연구에 사용된 교량의 지진취약도는 PGA 또는 PGV의 함수로 나타내어졌고, 1994년 Northridge 지진과 일련의 시나리오 지진에 대하여 교통망 손상 평가를 수행하였다. 또한 교량 보수 및 보강 후 교통망에 대한 피해정도를 정량화하기 위해 확률모델을 개발하였으며, 그 피해정도는 시간(Drivers Delay)으로 나타내었다. 본 연구가 캘리포니아를 대상으로 이루어져 국내적용 및 활용가능성에 대해서는 후속 연구가 뒤따라야 할 것으로 사료된다.

**주요어** : 지진, 액상화, 취약도곡선, 교량, 보수, 보강, 피해추정

### ABSTRACT

This paper describes a method of evaluating seismic system performance of highway transportation network in California. The basic element that plays a crucial role in this study is the fragility information of highway bridges in Caltrans' (California Department of Transportation) freeway network. The bridge fragility information is expressed as a function of the ground motion intensity, such as peak ground acceleration (PGA) or peak ground velocity (PGV). Network damage was evaluated under the 1994 Northridge earthquake and scenario earthquakes. A probabilistic model was developed to determine the effect of repair of bridge damage on the improvement of the network performance as days passed after the event. As an example, the system performance degradation measured in terms of an index, "Drivers Delay", is calculated for the Los Angeles area transportation system, and losses due to Drivers Delay with and without retrofit were estimated.

**Key words** : earthquake, liquefaction, fragility curve, bridge, transportation network, repair, retrofit, loss estimation

## 1. Introduction

Transportation systems including such facilities as highways, railroads, airports and harbors represent a critical component of the societal infrastructure systems needed not only for the welfare of the general public specifically for commercial, industrial and cultural human activities in national as well as international scale, but also for the purpose of facilitating transportation of search/rescue and medical teams, the injured to hospitals, repair and restoration news and materials and daily supplies for citizens under disasters. In this respect, under a natural or manmade disaster (e.g., earthquake, flood, etc.), it is critically important to maintain the transportation system to remain operational or repair and restore its function as soon as possible. Past experience showed too often that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can severely disrupt traffic flow, thus negatively impacting on the economy of a region as well as on the post earthquake emergency response and recovery activities. 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, this paper develops an analytical framework to integrate bridge and other structural performance with transportation network model in the context of seismic risk assessment by Shinozuka et al (2000).[1]

As mentioned above, highway transportation systems are comprised of numerous structural components and placed in equally complex natural and built environments. Among the engineered components, bridges are potentially the most vulnerable structural components under earthquake conditions.

The purpose of this research is to develop empirical

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본 논문에 대한 토의를 2004년 8월 31일까지 학회로 보내 주시면 그 결과를 게재하겠습니다. (논문접수일 : 2004. 3. 8 / 심사종료일 : 2004. 5. 11)

bridge fragility information expressed as a function of the ground motion intensity, such as PGA or PGV, and compare degradation of traffic capacity of Caltrans' (California Department of Transportation) network in Los Angeles and Orange County damaged by the 1994 Northridge earthquake. The method of network seismic risk evaluation is then developed by integrating the seismic hazard represented by the 1994 Northridge earthquake and system performance degradation caused thereby. In this study, the system performance degradation is measured in terms of an index, "Drivers Delay", that is calculated by equilibrium analysis of transportation systems (user optimizing deterministic assignment), on the basis of the 1991 Origin Destination (OD) survey performed for the region including Los Angeles and Orange County. This index is strictly used as a measure of network degradation under the unchanged OD matrix. In this sense, it does not precisely represent the network performance relative to the post earthquake traffic demand. This dynamic aspect of traffic flow problem is currently under study. Furthermore, under certain assumptions, the process and progress of bridge repair is simulated by a Monte Carlo method so as to produce a chronological improvement of post earthquake system performance. These simulations are all made utilizing the PGA spatial distribution of selected 47 scenario earthquakes from the regional seismic hazard associated with Los Angeles and Orange County. In addition, loss due to Drivers Delay is evaluated for the Caltrans' freeway network with and without retrofit, and finally loss due to ground shaking and liquefaction is evaluated for all bridges in Orange County with the aid of HAZUS software.[2]

## 2. Methodology

### 2.1 Highway system: Assessing structural component and network damage

Highway transportation systems are comprised of numerous structural components and placed in equally complex natural and built environments. Among the engineered components, bridges are the most vulnerable under earthquake conditions. In this respect, 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 to be an independent structure and determination of the degree of damage to each bridge can be treated as an independent statistical experiment.

The fragility curves by Shinozuka et al[3] are utilized to generate, in Monte Carlo simulation, the state of damage for each Caltrans bridge in Los Angeles and Orange County under postulated scenario earthquakes, and hence, the following analysis applies only to the bridge prior to the post Northridge retrofit.

The performance of the highway transportation system in Los Angeles metropolitan area in the event of the Northridge earthquake demonstrated some system resiliency that was activated by enlisting and integrating some seismically unaffected secondary highways and artillery streets into the expressway network that suffered from the loss of some of its bridges. For this reason, in this analysis, the alternate routes are considered to exist although they have lesser traffic capability in terms of both free flow speed and capacity compared to those associated with the segment or the link of the expressway they replaced. The link damage represents the worst state of damage to the bridges in that link (i.e., bottle neck hypothesis; if, for example, at least one of the bridges in a link suffers major damage, and if that is the greatest state of damage, the link has the major damage.). The values in Table 1 are hypothetical and future research is needed to validate them.

### 2.2 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 et al[1], the index used here is the "Drivers

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% |

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 for all network travelers on the damage network and that of 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) exhibits the calculation of the total daily travel time for all network users, in hours per day; as defined earlier, $x_a$ 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) exhibits the calculation of the Drivers Delay. The notation in Equation (2) is the same as in Equation (1) except that the primed variables denote the damaged network, and the unprimed variables refer to the original undamaged network. Note that "Drivers Delay", when calculated in this way, has units of hours per day. In order to obtain a total "Drivers Delay" with units 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, 1964:

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

where, $t_a^0$ is the travel time at zero flow on link $a$ (this is simply the link's length divided by the speed limit); $C_a$= is the "practical capacity" of the link, and $a$ and β are variable parameters. Ordinarily, and in this study, $a$=0.15 and β =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 patters. Therefore, traffic flow characteristics are approximates. In this context, we developed a method by which a large OD matrix can be reduced to a manageable size following Shiraki.[4] This method relies upon the Thiessen function (a ArcGIS software[5]) where the number of OD locations are reduced to the number of the nodes of the freeway network, each representing OD information within the Thiessen polygon developed around that node (see Fig 1). This significantly reduces the matrix dimension and makes the OD matrix usable in the PC based near realtime 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).

## 2.3 Determining effects of repair efforts

Earlier, it was noted that the calculated value of Drivers Delay was actually in terms of hours per day, and it would be necessary to integrate the delay over the time that it persists in order to have a measurement of the total delay. Notably, the Drivers Delay is not constant over the time it persists. Repair efforts improve the state of damage of the network, thus decreasing Drivers Delay over time. In this connection, this paper

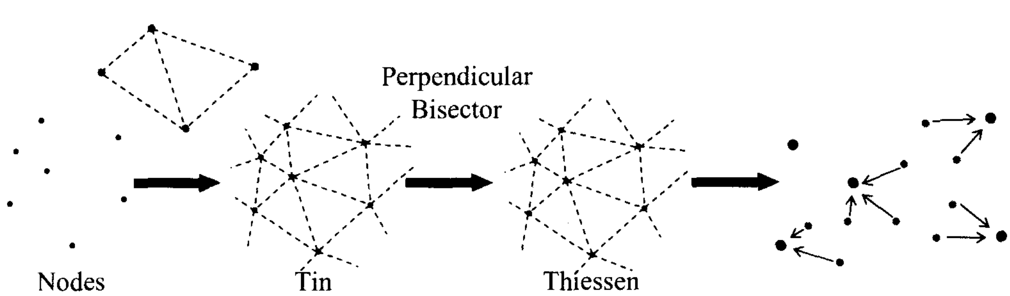


Fig 1 Making Thiessen Polygon

accounts for bridge repair process. Unfortunately, this is fairly difficult, as there is not much consistent and systematic data on the processes by which repair is conducted, and little documentation made available on the priorities selected by the engineers involved in the operation. Highway repair is conducted by and large using the best judgment of the engineers and management involved, and hence this process is not easily modeled. Nonetheless, a model is developed for this simulation to provide some numerical insight to the problem.

In this paper, the repair process is modeled as the time to complet a repair for each individual bridge damaged, and assumed to be a random variable uniformly distributed over travels ( $t_{i,\min}$ and $t_{i,\min}$) in which $i$=1, 2, 3 and 4 represent minor, moderate, major and collapse state of damage, respectively. For example, $t_{1,\min}$ = 10 days and $t_{1,\min}$= 150 days indicates a bridge that sustained a state of minor damage requires most optimistically 10 days and most pessimistically 150 days to complete repair. Otherwise, repair time takes a uniformly distributed value between these two values (see Fig 2). Chances are uniformly distributed for completion. Other values of subscript $i$ apply most optimistic and pessimistic times to bridges subjected to damage state. It is noted that the size and importance of bridges are not factored in this simplistic analysis, and are subject of future study.

Notice that the functions do not necessarily assume that all bridges can be repaired on Day 0, nor do they assume that the slopes (daily probabilities of repair) are the same. The choice of the parameters of the optimistic and pessimistic repair scenarios, (essentially, the first and last possible days a bridge of a given damage state can be repaired), are left to the best judgment of those developing the model. It is important to note that there are numerous ways that the repair of the system could be probabilistically modeled. For instance, link flow data could have been used to estimate the priorities for bridge repair. The method used here is chosen because there seems to be a correlation between the damage state of a bridge and the amount of time for a repair contract to be awarded, and for simplicity in simulation.

The repair process is simulated by another use of the Monte Carlo technique. Day 0 represents the day of the earthquake when the system has the greatest extent of damage. The data available includes the damage state of each bridge, as well as the damage state of link and the Drivers Delay. The bridge damage data is the relevant information for performing the repair simulation. Considering some arbitrary amount of time after the event, one can perform a Monte Carlo simulation in the same way as before with the repair distributions to determine if each bridge is repaired. This is done by considering each bridge one at a time. Based on the bridge's damage state, the time since the event, and the appropriate repair function for the damage state, one can use a random number generator to decide if the bridge is repaired. If the random value falls above the function for the given time since the event, it is not repaired; if it falls beneath the function, it is repaired. In this simulation, a repaired bridge shifts from its previous damage state directly to the no damage state, and its record is modified to reflect that change. This process is repeated for every bridge in this study region. The result is a system with an entirely different state of damage. Link damage state and the Drivers Delay must be recalculated to reflect the change to the system.

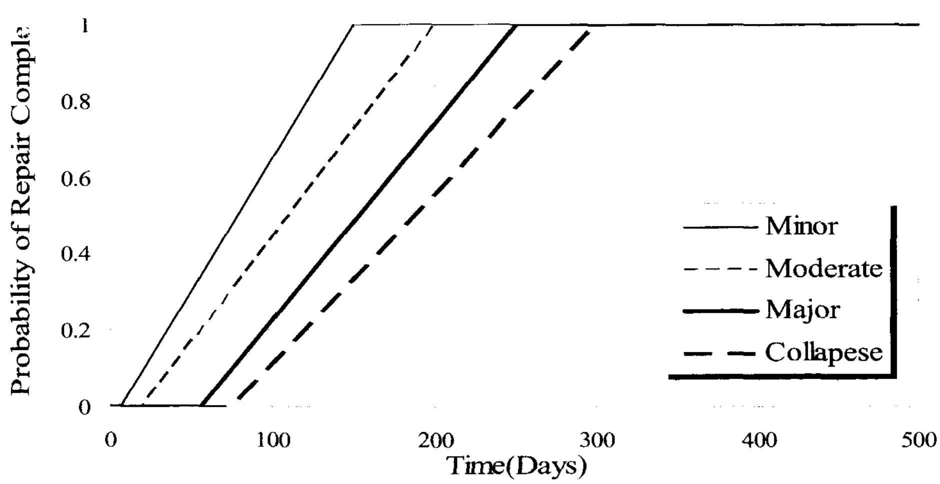


Fig 2 Probability distribution of functions used to model repair processes

### 2.4 Developing a risk measure

Given the possibility of performing multiple simulations for a study region, measures of risk for a spatially distributed highway system can be developed using the methods introduced in Chang et al.[6] 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 (in this case, Drivers Delay). A set of these is produced in the case study described later in this paper.

## 3. Application

### 3.1 Network model

Figure 3 displays the freeway and state highway network considered in this study. The study is limited to the freeway network in Los Angeles and Orange County in the Los Angeles Metropolitan Area.

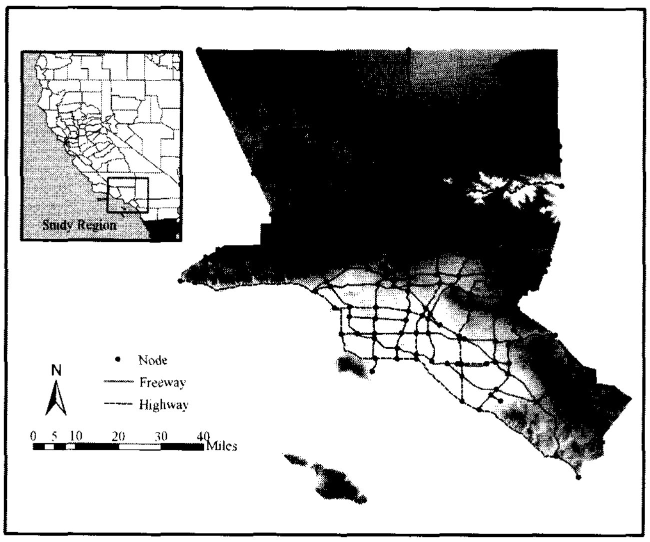


Fig 3 Los Angeles area highway network

This network model consists of 118 nodes and 185 links. The total number of bridges in this network is 2,727.

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 by 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 considered to be 65 miles per hour on freeway, and 35 miles per hour on the highway. 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 2,500 and 1,000 passenger car units per hour, respectively.

The spatial distribution of PGA and PGV values for the 1994 Northridge earthquake are acquired from the TriNet ShakeMap.[7] The bridge damage state is determined by Monte Carlo simulation based on the fragility information. The state of damage thus simulated for each bridge determines the link capacity as shown in Table 1 where the worst state of the bridge damage in the link determines the state of the link damage.

The Origin Destination (OD) data used in this paper consists of 1991 southern California OD survey results for 1,527 traffic analysis zone. The reader is referred to SCAG report[8] for the detail. As mentioned in the section on Methodology, Thiessen polygons are used to convert the 1991 SCAG survey data to node OD data of the freeway network shown in Fig 3.

### 3.2 Traffic analysis

To perform the traffic equilibrium analysis numerically, the method of user optimizing deterministic assignment described earlier is used with the aid of the incremental assignment technique. Figures 4 and 5 show the average result over the 10 simulations, including average damage state and average speed ratio. A speed ratio $\eta$ for each link, representing one measure of system performance degradation, is defined as:

$$\eta_a = \frac{S'_a}{S_a} \tag{4}$$

where, $\eta_a$ is the speed ratio on link $a$, $S_a$ is the flow speed on link $a$ under intact condition, $S'_a$ is the flow speed on link $a$ under damaged condition.

In the 1994 Northridge earthquake, Goltz[9] reported that bridges collapsed on I 10 (Santa Monica Freeway), on I 5 (Golden State Freeway), at I 5/SR 14 (Antelope Valley) intersection, and on SR 118 (San Fernando Valley). In the simulation, major or moderate damage to links are recognized at I 405, I 101 and I 210, as well as these four links (e.g. I 10, I 5, SR 14, SR 118). The differences between actual damage state and simulated result is caused by the bridge fragility information used in this study, where bridges are assumed to have a statistically homogenous vulnerability to earthquake damage, not reflecting the attributes of bridges such as skew, number of spans and soil conditions. When compared to the results based on PGA and PGV, only one different damage state is seen at I 5 and I 10. This is caused by the spatial distribution of PGA and PGV, and is not significant.

The computed average Drivers Delay is shown in Table 2. The Total travel time under intact condition is 8.90*10$^5$ hours. Drivers Delay based on PGA and PGV increased by 78% and 73% from the total travel time under intact condition, respectively. Drivers Delay based on PGV was 7% shorter than based on PGA, which is not a significant difference. This shows that if PGA or PGV are used consistently, the difference between the actual data and simulation network analysis is insignificant.

Table 2 Average Drivers Delay

| Case | Total Travel Time *10$^5$ (hours) | Drivers Delay *10$^5$ (hours) | Drivers Delay (min/PCU) |
|---|---|---|---|
| Simulation Based on PGA | 15.87 | 6.97 | 14.30 |
| Simulation Based on PGV | 15.40 | 6.50 | 13.34 |

*Total number of PCU (Passenger Car Unit) = 2,921,668

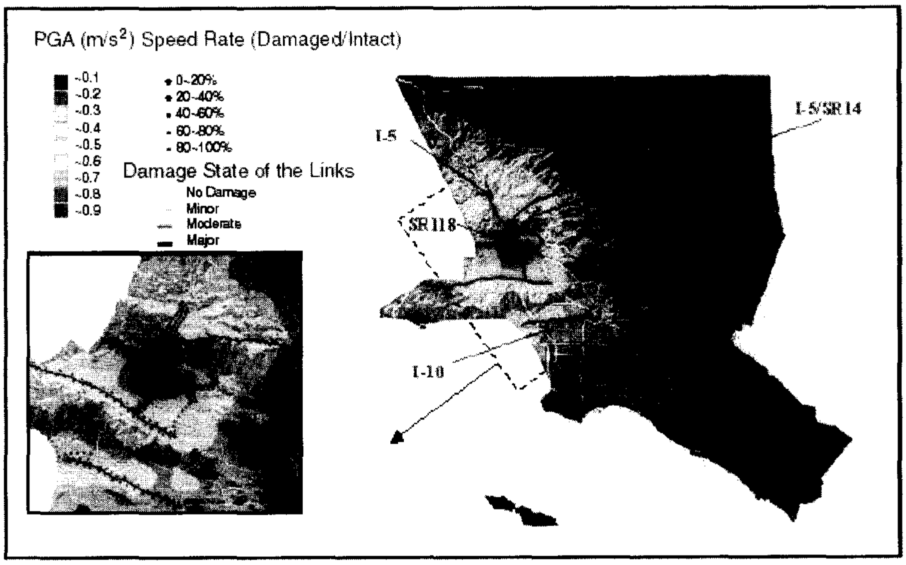


Fig 4 The 1994 Northridge earthquakes PGA distribution, average damage state of links, and average speed ratio of links (using bridge fragility information on the basis on PGA)

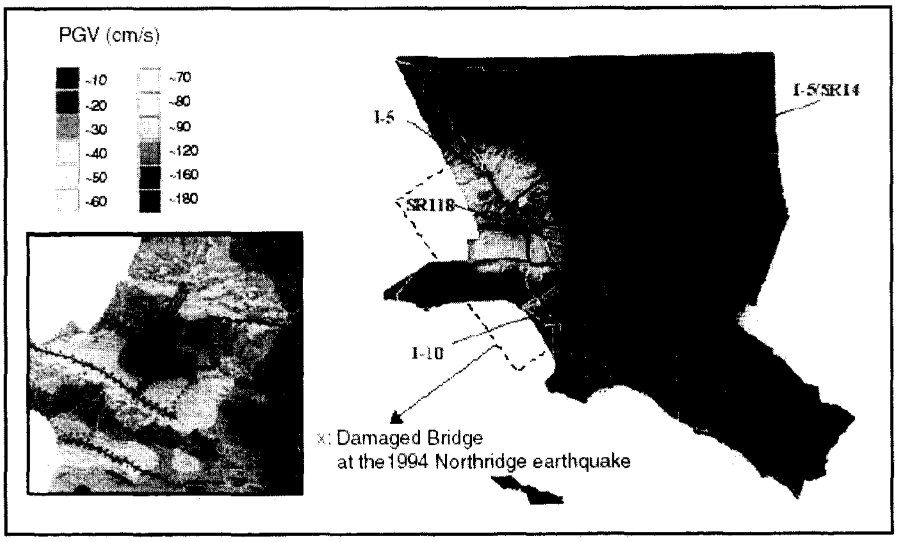


Fig 5 The 1994 Northridge earthquakes PGV distribution, average damage state of links, and average speed ratio of links (using bridge fragility information on the basis on PGV)

### 3.3 Risk curves for repair efforts

A set of 47 earthquake scenarios was considered, consistent with Chang et al.[6] The spatial PGA distributions for the selected event scenarios are modeled using the USC EPDAT (Early Post Earthquake Damage Assessment Tool) software, jointly developed by University of Southern California and EQE adapting original EPEDAT (Eguchi et al.[10]) to the present study.

The simulation is conducted by executing ten runs for each of the 47 earthquake scenarios. The Drives Delay results are then averaged for the purpose of offsetting the variability inherent in the implementations of the Monte Carlo method. The resulting data from each scenario's simulation includes: the damage caused to the network by the earthquake, the resulting Drivers Delay, and the variation of the Drivers Delay over time after the event. Using the Drivers Delay data and the calculated probabilities of exceedance for each scenario event, risk curves are then developed for the system.

Figure 6 plots the system risk curves for the Drivers Delay on Day 0, 28, and 84. Though there exists a good deal of noise in the Day 84 curve, it is apparent that the probability to exceed large Drivers Delays is virtually eliminated by 12 weeks after an event.

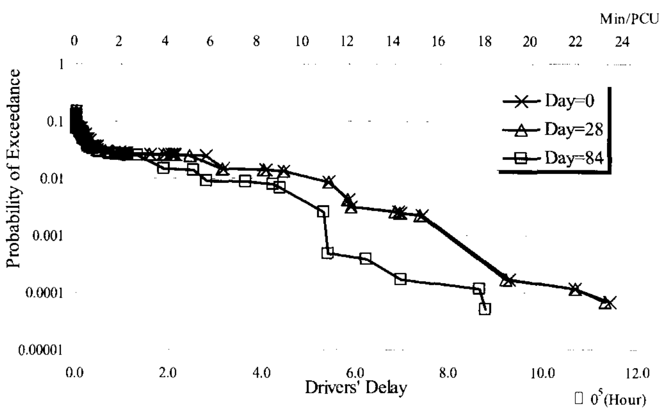


Fig 6 Risk curves, separated by time after event

### 3.4 Loss estimation

Similar simulations are performed for 47 scenario earthquakes using the bridge fragility information as a function of PGA with and without retrofit. The effect of retrofit is demonstrated by the ratio of the median values of the fragility curves for a retrofitted column to that of the column before retrofit (Shinozuka et al).[3] This ratio is referred to as fragility "enhancement". The fragility enhancement shows 55%, 75%, 104%, and 143% improvement for minor, moderate, major and collapse damage, respectively.

Figure 7 represents the fragility curves with and without retrofit. The fragility curves are represented by lognormal distribution functions with two parameters (median C and log standard deviation ζ) which are estimated with the aid of the maximum likelihood method. Figure 8 plots the risk curves for Drivers Delay with and without retrofit. The results of Drivers Delay based on enhanced fragility are reduced almost 90% over the results from without retrofit.

Furthermore, using these results, loss due to Drivers Delay is computed on the bases of $50 per one hour delay. Table 3 shows the results simulated for the representative scenario earthquakes. Estimated losses with retrofit are less than 10% of those without retrofit, and thus shows that the effect of retrofit is significant. Particularly, in the simulation for Malibu Coast, almost $50 million loss is avoided every day after the bridges are retrofitted, if repair is not made and if the same OD matrix is used.

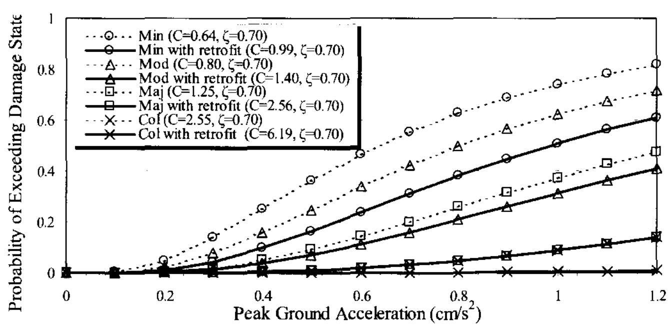


Fig 7 Fragility curve for with and without retrofit

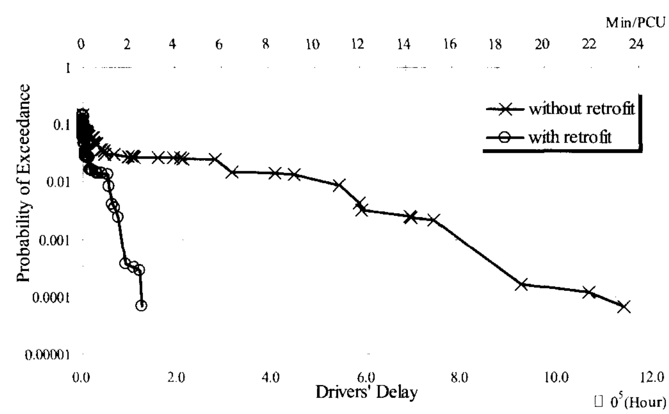


Fig 8 Risk curves of with and without retrofit

Table 3 Daily loss due to Drivers Delay (*$M)

| Scenario earthquake | Without retrofit | With retrofit |
|---|---|---|
| Newport Inglewood(S.) M7.0 | 04.74 | 0.27 |
| Newport Inglewood(N.) M7.0 | 10.60 | 0.98 |
| Elysian Park M7.1 | 15.73 | 1.02 |
| Malibu Coast M7.3 | 56.94 | 6.25 |

Also, as a preliminary study, loss estimation due to ground shaking and liquefaction is performed with the aid of HAZUS (1999) software.[3] In this estimation, 1,307 bridges including local bridges in Orange County CA, are studied. Utilizing HAZUS software, together with information available elsewhere for scenario earthquakes defined by MM (moment magnitude) and the liquefaction susceptibility map shown in Fig 9, permanent ground displacement (PGD) for lateral spread and ground settlement is evaluated. Integrating PGD, fragility information, damage ratio, replacement value and probability of liquefaction, loss due to liquefaction is estimated. For the present analysis, soil type is assumed to be stiff, and ground water depth is assumed to be five feet for the all bridges. Replacement value of $150 per deck area (square foot) from Caltrans data is used. The reader is referred to HAZUS Users' Technical Manual for the details. Table 4 shows the result of loss estimation. Loss due to ground shaking plus liquefaction is estimated by simply adding both losses to be conservative and the results are shown in Table 4. From the table, losses due to liquefaction are almost 55 % of loss due to ground shaking, and thus the effect of liquefaction is significant.

## 4. Conclusion

Integrating the bridge fragility information into the Monte Carlo analysis of traffic flows, degradation of traffic capacity of Caltrans' network in Los Angeles and Orange County damaged by the Northridge earthquake was evaluated. In the application examined, the simulation results are compared to the actual performance of Caltrans' network in the aftermath of the 1994 Northridge earthquake. The simulation results are very reasonable, and the choice of ground motion intensity, whether PGA or PGV, dose not significantly influence the network simulation results.

A probabilistic model was developed to evaluate the

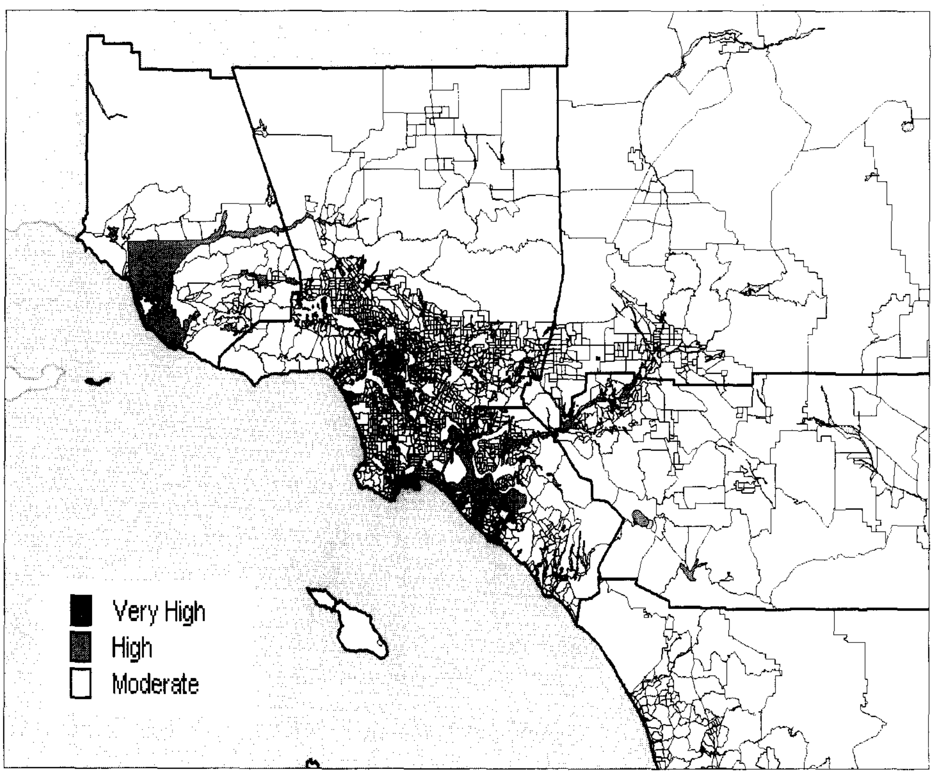


Fig 9 Liquefaction susceptibility map from EPEDAT (Eguchi, R.T., 1997)

Table 4 Loss due to ground shaking and liquefaction (*$M)

| Scenario earthquake | Ground shaking | Liquefaction | Ground shaking + Liquefaction |
|---|---|---|---|
| Newport Inglewood(S.) MM7.5 | 39.70 | 20.99 | 60.69 |
| Newport Inglewood(S.) MM6.9 | 29.27 | 15.97 | 45.24 |
| Elysian Park MM6.7 | 16.63 | 09.40 | 26.03 |

effect of bridge damage repair on the improvement of transportation network performance as days passed after the event. Notably, given the low probabilities of exceeding even moderate Drivers Delays, as evidenced by the risk curves, it can be said that the system exhibits remarkable resilience.

Losses due to Drivers Delay with and without retrofit are estimated. The results show that the effect of retrofit was significantly favorable, particularly in terms of reducing the loss avoided. Losses due to ground shaking and liquefaction were estimated with the aid of HAZUS software as a first step to incorporate PGD in the analysis. The effect of liquefaction is also an important factor to be taken into account in the transportation network simulation.

Future study is needed for the following subjects: dynamic aspects of traffic flow problems relative to post earthquake traffic demand; link damage definition and related link occupancy; modeling the repair process as a function of the size and importance of bridges; and perform uncertainty analysis to take advantage of the integrated insight acquired through this and other studies on modeling, numerical analysis and statistical interpretation.

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