UNIVERSITY OF CALIFORNIA,
IRVINE

Probabilistic post-earthquake restoration process with repair prioritization of highway network system for disaster resilience enhancement

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Civil Engineering

by

Tsutomu Nifuku

Dissertation Committee:
Professor Masanobu Shinozuka, Chair
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2015

DEDICATION

To

my family and wife, Yurie, in Japan

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Shinozuka, M., Cheung, K. P. and Nifuku, T. (2013). Intelligent damage mitigation for BWR nuclear reactors. 11th International Conference on Structural Safety and Reliability, New York, USA, June 16-20, 2013.

Nifuku, T. and Shinozuka, M. (2013). Code based reliability design of seismically isolated bridges. 11th International Conference on Structural Safety and Reliability, New York, USA, June 16-20, 2013.

Nifuku, T., Kawakami, Y. and Nakamura, T. (2011). A study of coseismic system outage under the condition of perfect correlation. 7th Japan Conference on Structural Safety and Reliability, Tokyo, Japan, October 12-14, 2011. In Japanese.

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Kawakami, Y., Nifuku, T., Nakamura, T. and Yamada, M. (2009). Seismic performance based design using a system reliability technique: part 2 methodology. Technical Paper of Annual Meeting of Architectural Institute of Japan, Sendai, Japan, August 26-29, 2009. In Japanese.

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Nifuku, T., Kawakami, Y. and Nakamura, T. (2008). Evaluation algorithm of outage time for business continuity planning. 57th Theoretical and Applied Mechanics Meeting of Science Council of Japan, Tokyo, Japan, June 10-12, 2008. In Japanese.

ABSTRACT OF THE DISSERTATION

Probabilistic post-earthquake restoration process with repair prioritization of highway network system for disaster resilience enhancement

By

Tsutomu Nifuku

Doctor of Philosophy in Civil Engineering

University of California, Irvine, 2015

Professor Masanobu Shinozuka, Chair

Comprehensive realization of post-earthquake restoration process for highway network considering repair prioritization are necessary for preparing effective countermeasures to restore transportation service and social activity in seismically active and automobile dependent regions like broader Los Angeles area quickly. Since the progress and the time to achieve full-recovery realistically change depending on repair orders and reconstruction works, restoration strategies without taking into account actual restoration phenomena negatively affect decision-making, efficient recovery, damage mitigation effort and network resilience enhancement.

For dealing with these concerns, a probabilistic model to simulate post-earthquake restoration process of highway network is developed with consideration of repair prioritization and reconstruction constraint in this research. Analytic Hierarchy Process, prioritizing algorithm, is used to decide bridge repair orders based on initial damage state due to earthquake and priority weight of four criteria; difficulty, importance, urgency and cost. Numbers of available construction labor around the target region is applied for constraint of repair work progress. The recovery passage of bridge, the critical component of highway restoration process, is modeled probabilistically based on Markov Chain process, Uniform distribution and Normal distribution. As performance of highway network, drivers' delay and trip opportunity loss over entire recovery period are estimated by conducting traffic network analysis through origin-destination matrix, gravity model and user equilibrium model considering the models of trip reduction and traffic demand recovery. The adequacy of developed model is then verified by the documented recovery records and loss estimations of Northridge earthquake.

As an application study, a regional possible scenario earthquake is applied to the established methodology implemented in the highway network system of Los Angeles and Orange counties. A number of simulations through Monte Carlo technique to express restoration processes corresponding to several repair prioritizations are presented by restoration curves and loss estimations. The analyzed results show that the developed procedure can simulate numerous thinkable recovery scenarios according to repair orders and contribute to decision-making for choosing the best suited repair prioritization for minimizing loss and maximizing resilience. Moreover, the basic scheme of this innovative technique can be applied to evaluation of restoration process of other infrastructure network systems and other disasters.

Chapter 1

Introduction

The correct understanding of post-earthquake restoration process of the vital infrastructure systems in society is necessary and beneficial for social activities and regional economy from the standpoint of disaster resilience enhancement. Highway transportation network is one of those basic infrastructures, and it is the most important public facility in seismically active and automobile dependent regions like the broader Los Angeles area as shown in Figure 1.1. This is because the rate of vehicle commute measure in this neighborhood, for example, is over 90% as listed in Figure 1.2. However, there are few researches which primarily focus on exploring recovery progress, though many researches regarding pre-earthquake preparations such as optimal aseismic retrofit or cost-benefit analysis of suited reinforcement are

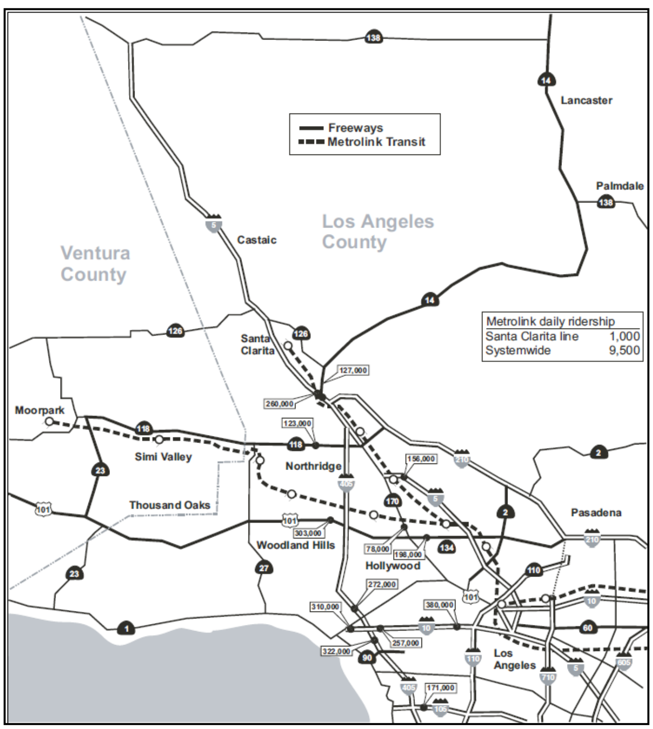


Figure 1.1 Highway in broader Los Angeles area (U.S. DOT & ITS, 2002).

	1990 Southern California	1990 Los Angeles County	1990 City of Los Angeles	2000 estimate Los Angeles County
SOV	72%	70%	65%	71%
HOV (2+)	15%	16%	15%	14%
Bus	4% (91%)	6% (92%)	10% (90%)	6% (91%)
Subway, rail	<1%	<1%	<1%	<1%
Walk, bicycle	4%	4%	5%	3%
Other*	4%	3%	4%	5%
Total	100%	100%	100%	100%

Figure 1.2 Rate of commute measure in Los Angeles area (U.S. DOT & ITS, 2002).

performed. Since it is very tough task to predict occurrence, epicenter and intensity of a specific earthquake, a kind of seismic damage is certain to happen no matter how much structures and systems are strengthened. Therefore, the evaluations of possible seismic damages and thinkable restoration processes should be carried out as well as pre-earthquake researches. If recovery actions with effective measure such as efficient repair prioritization cannot be adopted because of the lack of preparedness, the full recovery period will be prolonged and the damaged highway network will have severe influences on emergency activities, logistics chain, regional economy and so on. For instance, if decision maker gives more priority to ease of repair work than importance of road segment such as traffic volume, simple-repairable bridges having less traffic volume will get preference over tough-constructible bridges serving for more vehicle amount. In this case, physical restoration of bridges might be faster but traffic performance recovery is expected to take longer. Thus the preparedness of various simulations of recovery process according to repair prioritizations is useful for decision-making to respond to seismic damages.

For addressing these problems, a probabilistic analysis model to simulate post-earthquake restoration process is developed with consideration of repair prioritization and restriction of reconstruction labor based on past earthquake records and statistical data in this study. The post-earthquake process typically proceeds in an order shown in Figure 1.3. More specifically, it goes

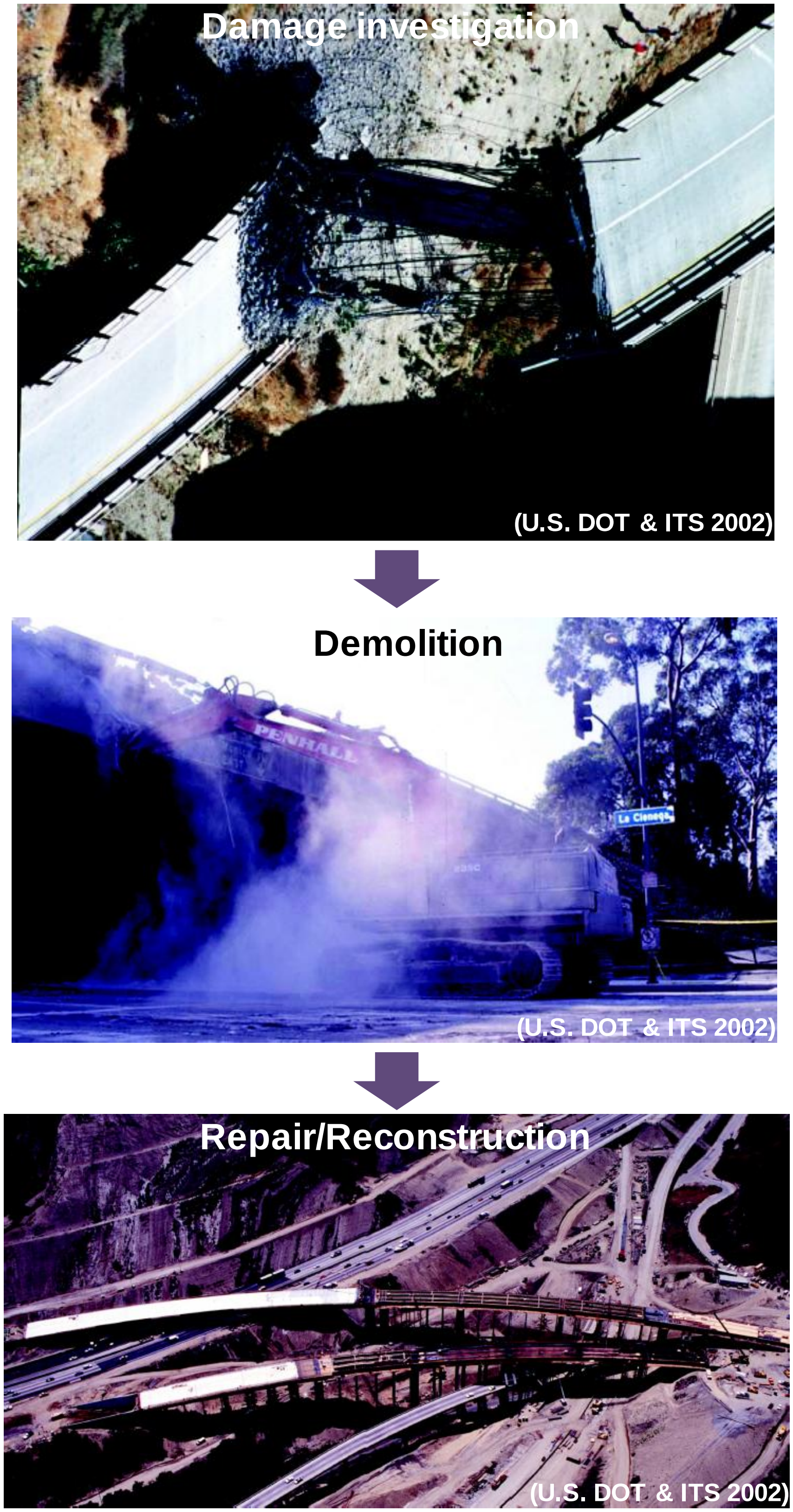


Figure 1.3 Typical post-earthquake progress (U.S. DOT & ITS, 2002).

along damage investigation, repair prioritization, repair work, gradual recovery and completion (U.S. DOT & ITS, 2002). Establishment of a realistic restoration model along this sequence is main purpose of this dissertation research by taking into account repair prioritization, reconstruction labor, bridge recovery model, loss estimation algorithm and traffic analysis. Traffic degradation of highway network over the recovery period is then estimated by this model in terms of social loss, which is summation of drivers' delay and trip opportunity loss (Zhou et al., 2010). For traffic analysis, origin-destination matrix, gravity model and user equilibrium model are applied to the highway network consisting of bridges, links and nodes modeled Los Angeles and Orange counties. The link damage depending on bridge damage state effects on residual traffic capacity of road segment after suffering seismic damage (Zhou, 2006). The bridge damage state is deterministically identified by bridge fragility and intensity of earthquake such as Peak Ground Acceleration (PGA) in this study. After repair orders are decided by prioritizing algorithm using Analytic Hierarchy Process (Nifuku & Shinozuka, 2014), the restoration process is probabilistically simulated through stochastic bridge recovery models such as Markov Chain process, Uniform distribution and Normal distribution based on limited regional workforce. Then, Monte Carlo technique is employed for recovery simulation at every time over the restoration period. The verification work by using actual records at Northridge earthquake is conducted for justifying the applicability of developed simulation model.

The simulated knowledge can help for finding the best suited decision for damage mitigation according to a certain situation by conducting loss analysis between the different restoration scenarios. This strategy is useful not only for traffic performance but also for social activities including economy over recovery period, because the seismic indirect loss induced throughout the restoration time sometimes becomes more costly than the direct physical loss

(Brookshire et al., 1997). Also, the proposed methodology can adjust well for disaster preparedness and damage mitigation effecting on disaster resilience in various unpredictable post-earthquake situations. Likewise the basic scheme of this established procedure can be applied to restoration assessments of other infrastructure systems and/or other disasters.

1.1 Problem statement

A kind of post-earthquake restoration prediction model with repair prioritization has not been presented explicitly for highway network systems even though a rapid recovery of traffic performance from disastrous event is a big concern in areas where people have to drive in daily life. There will most certainly be restoration works from disasters in varying degrees because some kinds of damages are inevitable. Therefore, unequivocal assessments of restoration process with repair prioritization make a large contribution to better repair decision, damage mitigation strategies and disaster resilience enhancement.

Various recovery scenarios should be preliminarily studied on a realistic restoration model so that decision-makers can determine the best repair order. Restoration process is typically expressed by two factors such as length of time and performance rate shown in Figure 1.4. The seismic loss during restoration term (i.e. resilience such as indirect loss) can be defined as the product of restoration time and performance loss as illustrated in green area in Figure 1.4 (Bruneau et al., 2003), and the total seismic loss is obtained as the sum of this loss and physical loss such as repair cost (i.e. direct loss). The amount of loss during restoration period is significantly affected by reconstruction progress according to repair order. Therefore, the haphazard repair order and the disorganized rehabilitation work make total period longer and induce uneconomical loss. Some research estimations of economic impacts due to a potential earthquake show that the loss due to regional activities' degradation after the earthquake accounts a significant proportion of total loss and some adjustments for refining resilience can greatly work for decreasing total disaster loss (Shinozuka et al., 1998 and Rose et al., 2011a & b). The traffic performance degradation becomes the worst level right after earthquake and the restoration work then starts immediately to achieve full recovery as expressed in Figure 1.4. Because the simulation sequences along actual phenomena shown in Figure 1.5 is obviously time-dependent process, transportation damage as the vital infrastructure system has to be recovered as soon as possible and the quick recovery facilitates restoration works for other infrastructure systems' damage in terms of conveyance of repair materials and attendance of

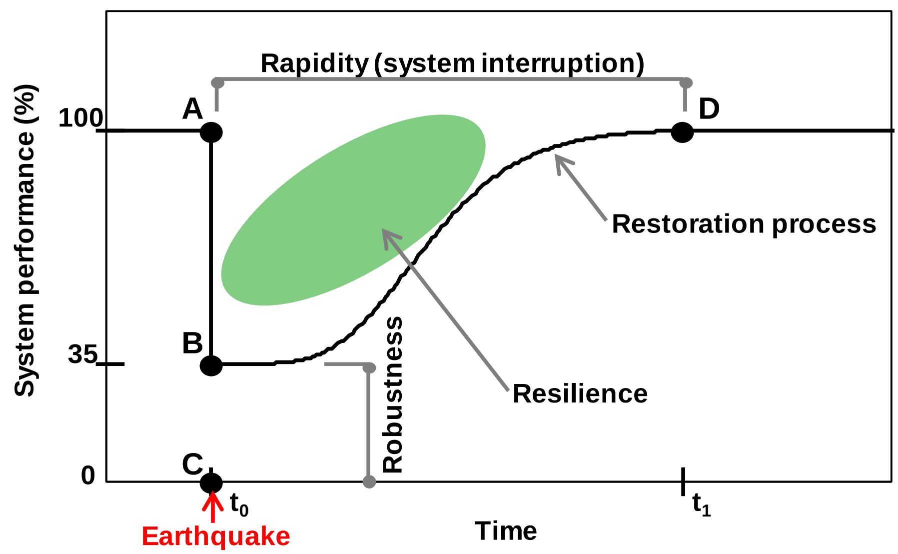


Figure 1.4 Post-earthquake recovery process represented by restoration curve.

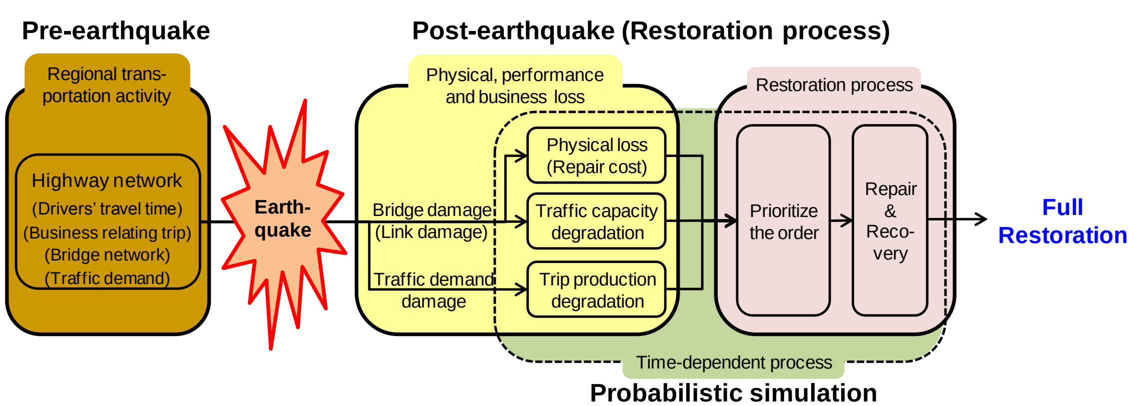


Figure 1.5 Probabilistic analysis sequence of restoration process.

reconstruction workers. Thus the post-earthquake restoration process of highway transportation network has to be studied preferentially in the target area of this research, Los Angeles and Orange counties.

In the case of proceeding a restoration work after suffering damage, if highway managing organizations did not simulate a number of possible restoration scenarios, they are unable to take effective countermeasures. The simulations should be re-examined periodically depending on social situation and highway network status at certain times and the analysis algorithms have to be updated by the latest findings, because no one can say enough about the preparedness for seismic damage. For instance, the restoration term and the number of damaged bridges at Northridge earthquake in 1994 were shorter and less than that at Loma Prieta earthquake in 1989, because the Loma Prieta experience had strengthened the preparation of highway network systems against seismic hazard (U.S. DOT & ITS, 2002). Also, in the case of Northridge earthquake, the restoration was completed faster than the anticipated period from chronological records of bridge reconstruction after Northridge earthquake (Caltrans, 1995). There were many reasons to accomplish such quick recovery. Those are that local agencies and constructors were familiar with their emergency countermeasures and the construction works were performed intensively to finish before scheduled time for both society and bonus. Thus actual progress of restoration process is supposed to change depending on situation of the time. Therefore, a newfangled estimation model can greatly help to mitigate damage and make decision because the total loss relates to both accurate restoration simulation and actual circumstances.

The proposed procedure in this dissertation advances the previous analytical framework (Zhou, 2006) by adding of repair prioritization algorithm, actual construction progress such as limited labor constraint, novel restoration model and verification with the documented records at

Northridge earthquake. These kinds of improvements should be made constantly in the sense of enhancing preparations for future disasters and scaling resilience of highway network system. This study also proposes the loss estimation regarding business and non-business caused by seismic traffic interruption because the time and monetary loss is persuasive and understandable in business scenes. Then the established and verified analysis methodology combined with all algorithms can trace a detailed post-earthquake restoration process over time.

1.2 Objective

For coping with the problems mentioned in the previous part, there are several challenges to address in addition to remodeling the highway transportation network model of Los Angeles and Orange counties shown in Figure 1.6 (Zhou, 2006). This research is not only to add new features and improve the previous model but also to verify the model by real records for making it more precise estimation, and the sophisticated highway restoration analysis is then conducted.

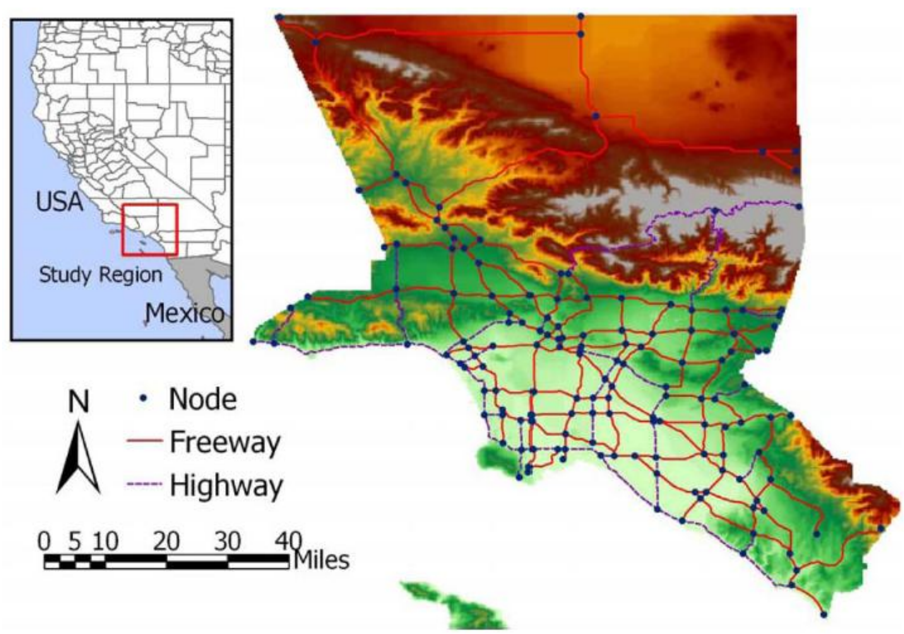


Figure 1.6 Highway transportation network model in Los Angeles and Orange counties (Zhou, 2006).

The itemized research flow is indicated in Figure 1.7. The basic analysis sequence is in order of the estimation of scenario earthquakes' intensity (i.e. Peak Ground Acceleration; PGA), the initial seismic damage detection of bridges and links, the prioritization of repair order based on initial damage state and priority criteria, the recovery simulation with transportation analysis over time, the performance estimation of highway network (i.e. drivers' delay and trip opportunity loss) and the estimation of business and non-business loss related to traffic degradation. The verification of established model is made by actual data of seismic damage and reconstruction work at Northridge earthquake. The pre-earthquake transportation analysis is also conducted for comparison with post-earthquake damaged situation.

The detailed study framework following the analysis sequences is drawn in Figure 1.8, and the particular descriptions are stated for several major topics in the figure. This research approach is founded on multidisciplinary study, such as earthquake engineering, structural engineering, transportation engineering, stochastic and statistical procedure, social science and

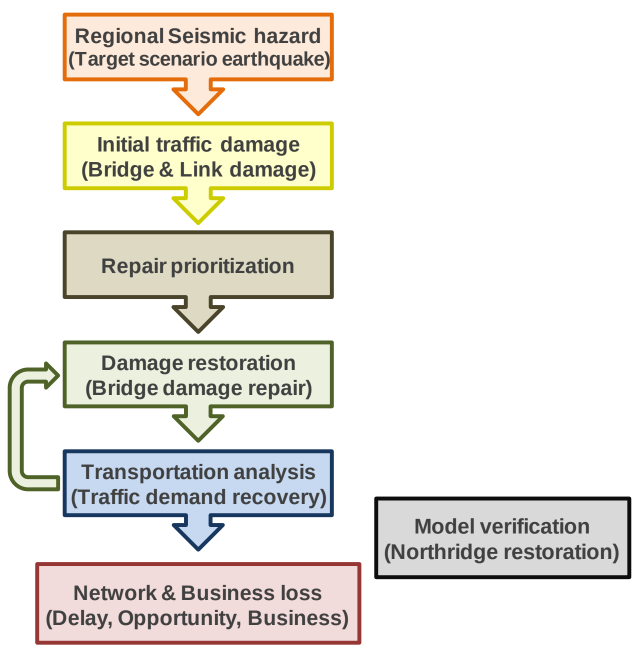


Figure 1.7 Itemized research flow.

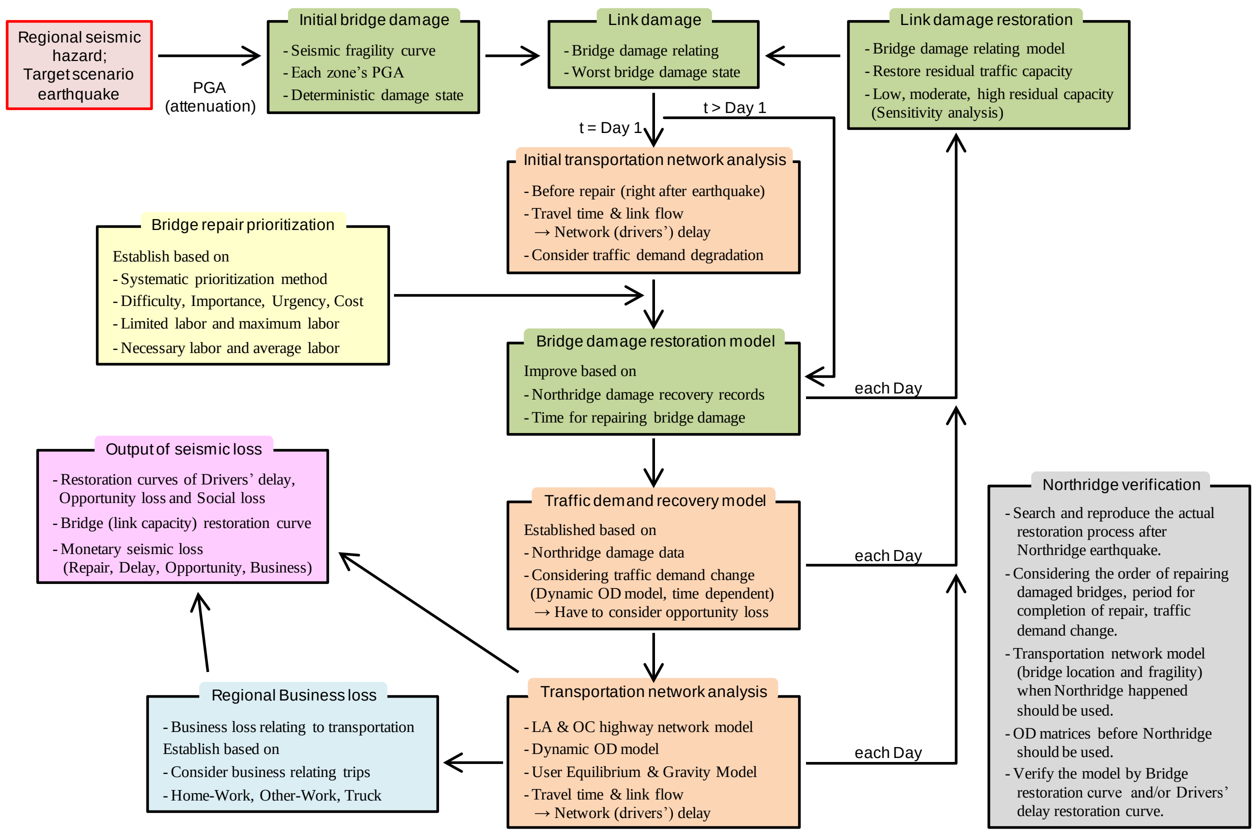


Figure 1.8 Detailed study framework and process flow.

economics. The specific investigations, solving methods and mathematical expressions for accomplishing the challenges, are presented in the following chapters. In chapter 2, the integrated model of highway network system is remodeled on the basis of the previous study (Zhou, 2006). The ideas of regional seismic hazard, bridge seismic fragility, highway link damage, residual traffic capacity and highway traffic analysis are explained. The drivers' delay and trip opportunity loss for representing highway performance are introduced, and they are divided into business and non-business loss relating to traffic damage. Chapter 3 tackles repair prioritization, reconstruction constraint and bridge restoration model in the method of mathematical way, statistical way and probabilistic way, respectively. The Analytic Hierarchy Process (AHP) is applied to prioritization algorithm for developing a comprehensive and systematic method which can consider several realistic criteria for deciding repair order. The limited regional labor is considered to constrain post-earthquake reconstruction work for reflecting practical reality, and the number of available workforce is calibrated by Northridge earthquake records. The Markov Chain process model which can estimate the repair status over each time step is developed in addition to the existing models such as Uniform distribution model and Normal distribution model for simulating bridge restoration process. The transition probability matrix of Markov Chain process is obtained by calibration analysis with Northridge earthquake records. The restoration process considering these algorithms is simulated through Monte Carlo technique in this study. The verification work of this established analysis model is done in chapter 4. The applicability of restoration process and loss estimation by the model is confirmed by comparing the analyzed result with the economic loss and additional driving time due to Northridge earthquake highway damage estimated by Gordon (Gordon et al., 1998). The simulation of Northridge earthquake is conducted by using actual documented records of the spatial distribution of earthquake intensity, the bridge damage at Northridge earthquake, the assumed repair order and the calibrated reconstruction constraint. In chapter 5, a scenario earthquake application is shown as an example of practical utilization. A potential scenario

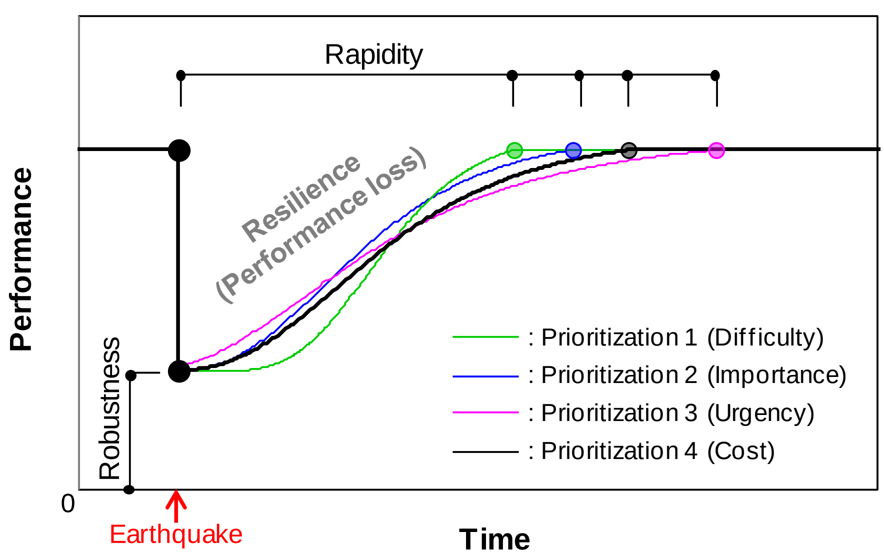


Figure 1.9 Conceptual figure of restoration curves corresponding to repair priorities.

earthquake in Los Angeles and Orange counties, Newport-Inglewood fault earthquake, is applied to the model, and the entire simulation process is run through based on six repair prioritizations. The evaluated highway performance is then expressed in the form of restoration curve as illustrated in Figure 1.9, and the seismic loss due to impairment of highway function is accumulated in time and monetary value. These results can help to make a comparative review of preferable restoration process. Also, the sensitivity analysis under the same earthquake is carried on considering three levels of residual traffic capacity. Lastly, chapter 6 concludes this research by summarizing the considerable accomplishments and stating the further necessary studies.

Chapter 2

Highway network system

The highway network model in Los Angeles and Orange counties is used for simulating the functionality of highway transportation network in this study. The model has been originally developed by several continuous researches (Shiraki et al., 2000 & 2007, Shinozuka et al., 2003 & 2005, Zhou, 2006 and Zhou et al., 2010) based on the southern California Origin-Destination (OD) survey data consisted of 6 trip types such as Home-Work, Home-Other, Other-Other, Other-Work, Home-Shop and Truck trip. In this study, several innovated analytical capabilities are established and added to this model. A number of components such as bridges, links (i.e., road segments), nodes (i.e., interchanges) and zones (i.e., OD zones) build this model as a spatially distributed network system, and they cooperate to make highway network operate. Since the model components are located all over the network area, the simulation should be a scenario-based analysis to reflect the spatial distribution of seismic intensity of earthquake. Also, the estimation of a specific potential earthquake can help people to imagine seismic damage easily. Therefore, scenario earthquakes occurred potentially in the area are applied to estimate post-earthquake effects of all components consisting the highway network model, and traffic analysis is then performed based on their damage status until the traffic functionality is fully recovered. The traffic impairment is investigated in the forms of performance loss represented by time and economic loss, and these losses are divided into business and non-business losses.

2.1 Highway network model

The highway network model is consisted of 3,133 bridges, 231 links, 148 nodes and 148 OD zones as shown in Figure 2.1. All links are connected to each other through nodes which represent corresponding OD zones. Bridges are arranged on links on the basis of their actual location on road segments, so there are some links which do not have any bridges in this model. The original number of OD data (i.e., zones) investigated by the southern California OD survey is 3217, which means that the scale of OD matrix is a 3,217 by 3,217. The large matrix is then condensed to a 148 by 148 matrix by the Thiessen function within the Arc/Info geographic information system (ArcGIS, 2009) for adjusting to this study and being the matrix size to manageable and computable number, and each OD data are also summarized to respective zones. Link is categorized into two types, freeway and highway. The speed limit of a freeway link without traffic signal is assumed to be 65 miles per hour (mph) and that of a highway link with traffic signal is 35 mph. The maximum capacity of a lane of freeway link is presumed to be 2,500 passenger car unit (PCU) and that of highway link is 1,000 PCU. The traffic capacities of each links are then calculated by these conditions and other road information like lane numbers.

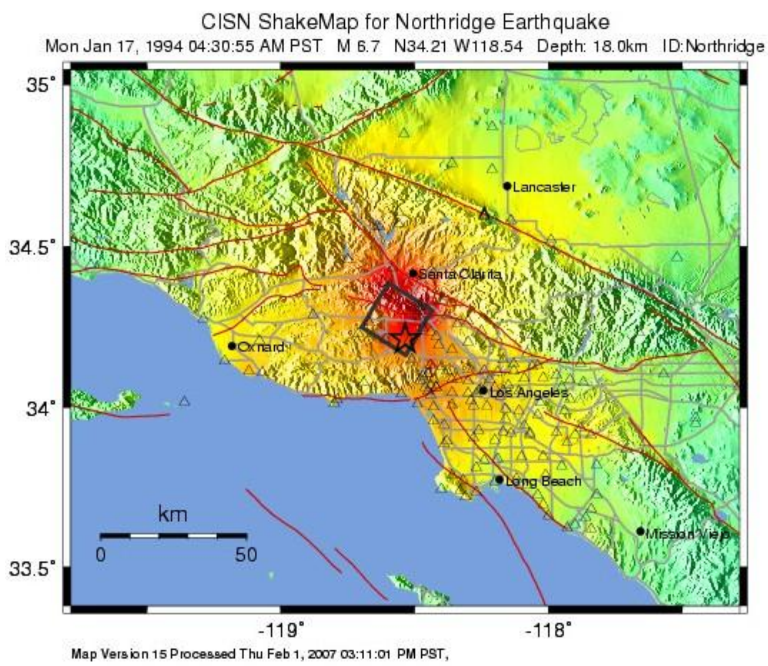
Figure 2.1 Highway transportation network model.

2.2 Seismic hazard

The proposed methodology uses particular earthquakes such as scenario earthquakes for seismic hazard to simulate post-earthquake process. Locations, depths, intensities and characteristics of scenario earthquakes and characteristics of the soil of bridge sites are therefore assumed specifically to estimate deterministically the mean value of Peak Ground Acceleration (PGA) of all bridges' sites by employing empirical attenuation function. PGA value is then input into the identification algorithm of initial bridge damage state. In this study, two scenario earthquakes are utilized. One of them is Northridge earthquake occurred in 1994 for the purpose of model verification. Since this is the actual earthquake, the observed PGA intensities of Northridge earthquake are applied to the model. Another one is Newport-Inglewood scenario earthquake for simulating the restoration process of highway network as an application example. This is one of regional possible scenario earthquakes, and the PGA values due to this potential earthquake are estimated through the algorithm of attenuation function.

2.2.1 Northridge earthquake

Northridge earthquake occurred in broader Los Angeles on January 17, 1994. The earthquake was centered about 30 km northwest of Los Angeles in the San Fernando Valley, and the focal depth was estimated at about 15-20 km. The main-shock occurred on an undefined thrust fault, near the Frew and Santa Susana faults. This earthquake had moment magnitude (Mw) of 6.7 and the strongest horizontal PGA of about 1.0g observed near the epicenter. The tremendous damage was caused to human life, infrastructure systems, buildings and economic activities by the earthquake, and the estimations and reports of Northridge earthquake indicate that this is the most costly natural disaster in the United States (NIST, 1994). One thing, however, is positive. That is many kinds of characteristics and aftermath of this earthquake were recorded and retained because of its extensiveness. Then, numerous researches, studies and analyses were made in the fields of seismology, geotechnique, structural engineering, civil engineering, social science, economy, etc.. Therefore, those documented information regarding Northridge earthquake can be used for verifying the applicability of the model developed in this study. The PGA distribution at Northridge earthquake estimated with the recorded data is shown in Figure 2.2 (U.S. Geological Survey; USGS ShakeMap). This PGA distribution and the earthquake intensity at highway bridge sites recorded by California department of transportation (Caltrans) are applied to the verification study.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 2.2 PGA distribution at Northridge earthquake (USGS ShakeMap).

2.2.2 Regional possible scenario earthquakes

This methodology is a scenario-based analysis as mentioned before, so particular earthquakes are applied to damage identification, repair prioritization and recovery estimation.

In this study, a set of probabilistic scenario earthquakes developed for seismic risk analysis of spatially distributed systems by Zhou and Shinozuka (2006) is used. It was estimated for the area of Los Angeles county and a part of Orange county where the modeled highway network locates (Zhou & Shinozuka, 2006 and Zhou, 2006). Those scenario earthquakes consist of both faults sources and background seismicity. Faults sources are based on characteristic earthquake model and truncated exponential model, and background seismicity is founded on truncated exponential model by using historical seismicity. 151 fault scenarios and 44 background scenarios were then generated and were confirmed to match well to hazard points estimated by USGS. For being computable number of scenario earthquakes without losing seismic hazardous possibility, a small set of scenario earthquakes with properly assigned annual occurrence probabilities are selected to represent the regional seismic hazard (Zhou, 2006 and Chang et al., 2000). This concept is expressed in the form of risk assessment as follow:

$$\overline{L} = \sum_{k=1}^{K} l(S \mid E_k) p(E_k) \cong \sum_{m=1}^{M} l(S \mid E'_m) p'(E'_m), (M << K) \quad (2.1)$$

where $\overline{L}$ is the annual expected loss due to seismic hazard, $l(S|E)$ is the loss due to earthquake, $p(E_k)$ is kth scenario earthquake's annual frequency of occurrence, $p'(E'_m)$ is mth selected scenario earthquake's annual frequency of occurrence, k is the total number of scenario earthquakes and m is the number of selected scenario earthquakes. 49 characteristic scenarios, 6 faults scenarios and 8 background scenarios were eventually selected for probabilistic scenario earthquakes as representative seismic hazard in this region from all scenarios. The final set of probabilistic scenario earthquakes are shown in Table 2.1. For identifying the intensity of specific earthquakes at specific sites, PGA at each bridge locations for every scenario earthquakes are then estimated by attenuation relationship.

Table 2.1 Regional seismic hazard: probabilistic scenario earthquakes in the region.

No.	Fault name	Magnitude	Annual Frequency	Latitude	Longitude
1	San Andreas 1857	7.8	4.70E-03	-	-
2	Anacapa-Dume	7.5	9.47E-04	-	-
3	Big Pine	6.9	5.09E-04	-	-
4	Channel Island Thrust	7.5	4.83E-04	-	-
5	Chino Central Ave.	6.7	1.13E-03	-	-
6	Clamshell	6.5	6.85E-04	-	-
7	Cleghorn	6.5	4.64E-03	-	-
8	Coronado Bank	7.6	7.68E-04	-	-
9	Cucamonga	6.9	3.01E-03	-	-
10	Elsinore: Whitter	6.8	1.56E-03	-	-
11	Elsinore: Glen Ivy	6.8	2.94E-03	-	-
12	Elsinore: Temecula	6.8	4.17E-03	-	-
13	Elsinore: Julian	7.1	2.94E-03	-	-
14	Garlock W.	7.3	2.12E-03	-	-
15	Helendalo	7.3	2.27E-04	-	-
16	Hollywood	6.4	1.48E-03	-	-
17	Holser	6.5	5.33E-04	-	-
18	Lenwood-Lockhart	7.5	1.70E-04	-	-
19	Malibu Coast	6.7	3.44E-04	-	-
20	Mission Ridge	7.2	1.75E-04	-	-
21	San Andreas Majave	7.4	2.05E-03	-	-
22	Newport-Inglewood	7.1	3.42E-04	-	-
23	Newport-Inglewood off	7.1	7.70E-04	-	-
24	North Frontal W.	7.2	3.89E-04	-	-
25	Northridge	7.0	5.77E-04	-	-
26	Oak Ridge Offshore (Thrust)	7.1	1.40E-03	-	-
27	Oak Ridge Onshore	7.0	2.32E-03	-	-
28	Palo Verdes	7.3	7.49E-04	-	-
29	Pleito	7.0	2.23E-03	-	-
30	Puente Hill Thrust	7.1	2.34E-04	-	-
31	Raymond	6.5	2.13E-03	-	-
32	Red Mountain	7.0	9.89E-04	-	-
33	Rose Canyon	7.2	5.78E-04	-	-
34	San Andreas S2	7.7	4.70E-03	-	-
35	San Cayetano	7.0	3.20E-03	-	-
36	San Gabriel	7.2	2.64E-04	-	-
37	San Joaquin Hill	6.6	7.07E-04	-	-
38	San Jose	6.4	8.73E-04	-	-
39	Santa Monica	6.6	1.23E-03	-	-
40	Santa Susana	6.7	5.15E-03	-	-
41	Santa Ynez E.	7.1	1.01E-03	-	-
42	Sierra Madre	7.2	5.80E-04	-	-
43	Sierra Madre SF	6.7	1.54E-03	-	-
44	Simi Santa Rosa	7.0	5.07E-04	-	-
45	San Jacinto: San Bernardino	6.7	1.00E-02	-	-
46	San Jacinto: Valley	6.9	1.21E-02	-	-
47	Upper Elysian Park	6.4	2.27E-03	-	-
48	Verdugo	6.9	3.12E-04	-	-
49	White Wolf	7.3	8.44E-04	-	-
50	Newport-Inglewood	6.8	4.82E-04	33.798	-118.168
51	Northridge	6.7	8.13E-04	34.339	-118.549
52	Palo Verdes	6.9	1.49E-03	33.801	-118.346
53	Puente Hill Thrust	6.8	3.29E-04	33.943	-118.093
54	San Gabriel	6.8	5.26E-04	34.472	-118.604
55	Sierra Madre	6.8	1.15E-03	34.175	-118.021
56	Background 1	6.5	1.00E-02	34.663	-117.912
57	Background 2	6.5	1.00E-02	34.444	-118.273
58	Background 3	6.5	1.00E-02	34.723	-118.451
59	Background 4	6.5	1.00E-02	34.571	-118.723
60	Background 5	6.5	1.00E-02	34.392	-118.607
61	Background 6	6.5	1.00E-02	34.072	-118.859
62	Background 7	6.5	1.00E-02	33.777	-118.352
63	Background 8	6.5	1.00E-02	33.515	-117.720

For the scenario earthquake application described in chapter 5, a scenario earthquake, Newport-Inglewood fault earthquake Mw7.1 highlighted by gray in Table 2.1, is chosen from 63 probabilistic scenario earthquakes. This is because the expected damage caused by this earthquake is supposed to be tremendous (Zhou, 2006). Its moment magnitude is assumed 7.1 and the annual frequency of occurrence is estimated 0.000342. The location of fault is directly below the metropolitan area of the broader Los Angeles, and the fault length of this earthquake is about 50 miles from Newport Beach to Culver City. The stronger PGA distribution of this earthquake estimated by attenuation relationship is spreading from the center of Long Beach as drawn in Figure 2.3. Based on this PGA distribution, the initial damage status of highway network is identified and the application example for restoration process simulation is conducted and shown in chapter 5.

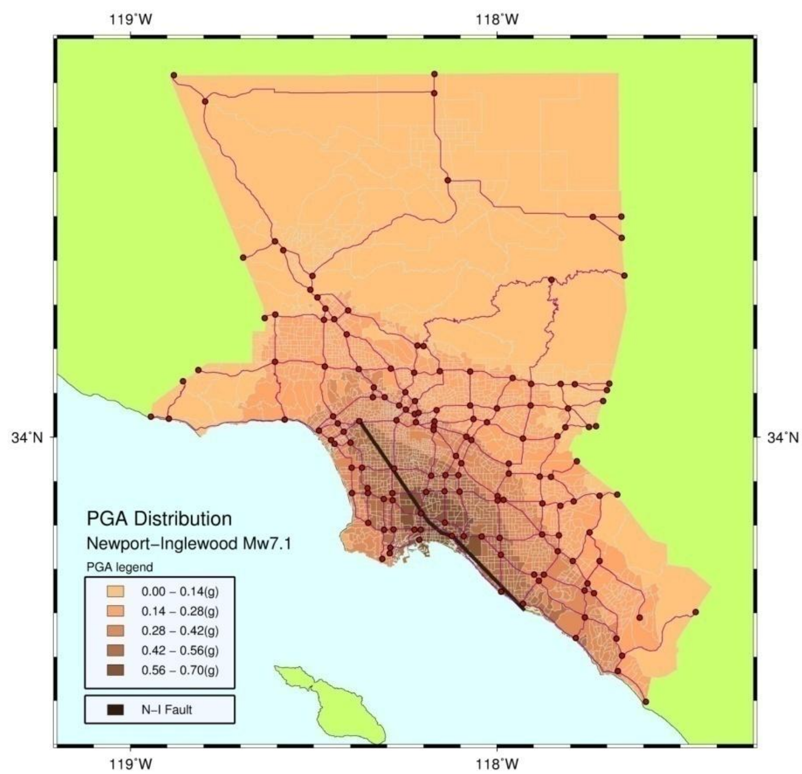


Figure 2.3 PGA distribution at Newport-Inglewood Mw7.1 scenario earthquake.

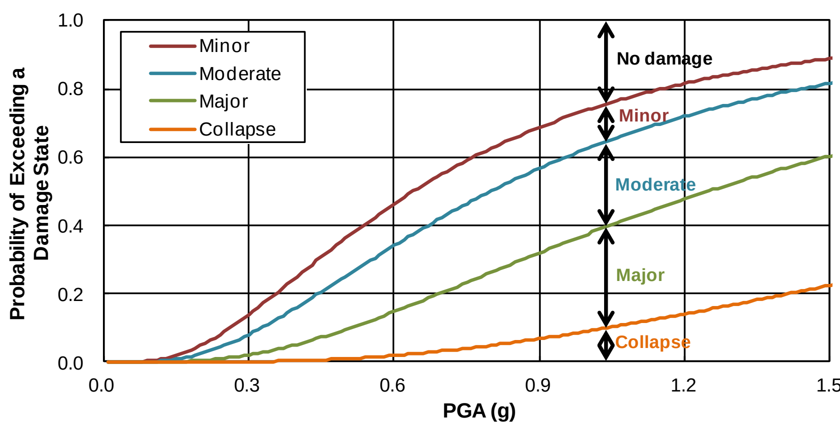
2.3 Highway bridge damage

There are many elements which constitute highway network such as roadway, bridge, retaining wall, embankment, tunnel and so forth. It is true that all of them are supposed to be suffered some kinds of damage caused by earthquake. However, bridge is the most fragile and the highest influential element in highway transportation system under seismic events as the damage histories at past disastrous earthquakes demonstrated. Therefore, bridges allocated in links are assumed to only represent seismic vulnerability of the highway network in this study. In addition, the bridge damage is induced by several seismic external forces such as ground shaking, ground failure, liquefaction and ground lateral flow. However, the external forces excluding ground shaking are strongly affected by soil conditions and geographic characteristics at sites, and bridges built at those sites are usually prepared sufficient reinforcement measures to those seismic effects. Therefore, ground shaking is only considered as an index for assessing bridge damage state in this study (Zhou, 2006).

For identifying bridge damage, the empirical bridge fragility curve and the intensity of ground shaking such as PGA induced by scenario earthquake at each bridge site are used. The fragility curve is defined as a function of failure probability according to intensity of earthquake and is expressed by log-normal distribution function as follow (Ang & Tang, 2006):

$$F(a) = \Phi\left[\ln(a/c)/\varsigma\right] \tag{2.2}$$

where *F(.)* is the fragility curve, *a* is PGA value, *c* is median value of damage state, ζ is log-standard deviation of damage state and Φ(.) is standard normal distribution function. Thus, the damage state of bridge is identified by PGA value in form of fragility curve, and probability of exceeding each bridge damage states can be then read from the curve. The empirical bridge fragility curves used for this study were statistically estimated by a number of bridge damage data and corresponding PGA values in Los Angeles area at Northridge earthquake as shown in Figure 2.4 (Shinozuka et al., 2005). Those characteristic values of log-normal distribution were derived by using maximum likelihood method and damage states were classified 5 into no damage, minor, moderate, major and collapse (Nakamura et al., 1998 and Shinozuka et al., 2000a, 2000b & 2007). Though bridge damage prediction should be determined with consideration of uncertainty about damage status, the bridge damage state is, here, deterministically resolved based on the bridge fragility curve and earthquake intensity. This is because the proposed methodology deals with the recovery progress after earthquake happens, which means the damage state has been already identified and the simulation algorithm focuses on randomness of network's restoration process according to repair prioritizations.



Damage State	PGA (g)	
	Median	Log S.D.
Minor	0.64	0.70
Moderate	0.80	0.70
Major	1.25	0.70
Collapse	2.55	0.70

Figure 2.4 Empirical bridge fragility curves (Shinozuka et al., 2005).

2.4 Highway link damage

The damage of the highway network link is assumed to correspond to the worst damage state of bridges located in a link based on bottleneck hypothesis in this study. As illustrated in Figure 2.5 as an example, if the severest damage state of bridges in a link were moderate, the link damage state is determined to be moderate. Since the link damage state is corresponding to the bridge damage status, it will be updated according to the repaired bridge damage state at each time during the entire restoration period as bridge repair work progresses. Then, the link damage state effects on the degraded capacity of highway transportation due to seismic damage explained in the following section.

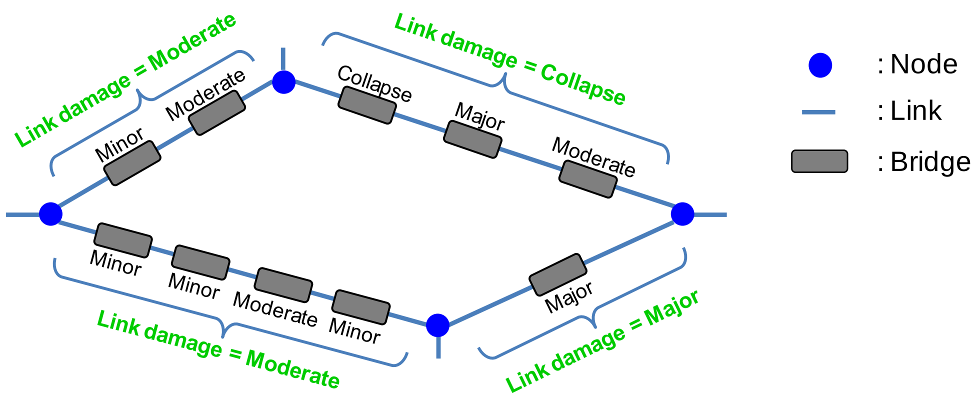


Figure 2.5 Highway link damage based on bottleneck hypothesis.

2.5 Residual traffic capacity

The traffic capacity of roadway will obviously decrease if it suffers seismic damage on some level. However, in that case, detours such as alternate roads are immediately provided to the closed main route as the post-earthquake activities taken by Caltrans at Northridge earthquake indicate. For example, the initial detours using local streets were established during the first 12 days following the earthquake for the closure of the intersections on Interstate 5 and State Route 14 due to collapsed bridges. Then, those detours were changed to other roads continually considering the progress of reconstruction works and were managed appropriately according to vehicle occupancy rate and/or transportation purpose by the all relating operators (Caltrans, 1994a, 1994d, 1994e & 1995). This redundancy of highway network performance should be integrated into the analysis model although the traffic capacities of detours are less than that of original highway segments. In this study, the assumed residual rates to the capacity of intact situation are used as shown in Table 2.2, and these rates are originally proposed to all link damage states by a previous research (Shinozuka et al., 2005) and consider the traffic capacity of detours for collapsed links. Three levels of residual rates, Low, Moderate and High, are prepared to conduct the sensitivity analysis of the rates to traffic, because these parameters are hypothetical and are needed to explore. However, there is a description about analyzed residual capacities that says the appropriate reduction rate is averagely 60% (Zhou, 2006).

Table 2.2 Residual traffic capacity corresponding to link damage state.

	Link residual traffic capacity ratio (%)		
Link damage	Low	Moderate	High
No	100	100	100
Minor	100	100	100
Moderate	25	50	75
Major	10	25	50
Collapse	10*	25*	50*

*Local detour route considered.

The link performance considering the reduced traffic capacity is determined by the travel time for link depending on the flow rate of link. The performance is then expressed as follow:

$$t_a = t_a^0 \left[1 + \alpha \left(x_a / C_a \right)^\beta \right] \tag{2.3}$$

where t_a is travel time at flow x_a on link a, x_a is traffic flow on link a (i.e., volume), $t^0{}_a$ is travel time at free flow on link a, C_a is traffic capacity of link a, α is typically 0.15 applied and β is generally 4.0 used.

2.6 Highway traffic analysis

Highway traffic analysis in this study integrates the trip reduction model reflecting decreased trip numbers due to seismic damage, the gravity model for generating trip distribution and the user equilibrium model for solving traffic assignment problem to estimate network travel time and traffic flow. The integrated analysis is conducted by following Evans formulation (Evans, 1976), and the equilibrium condition is based on Wardrop's 1st principle. The origin-destination matrix of pre-earthquake situation is created from the southern California origin-destination survey data, and the origin-destination matrix at post-earthquake damaged status is renewed by trip production and attraction with consideration of trip reduction rate. The integrated algorithm adjusts the origin-destination matrix and link volume simultaneously with application of two consecutive iterations (i.e., the iterative secant method), and it finally estimates traffic volume and congested travel time of highway network (Zhou, 2006).

2.6.1 Origin-destination data

The origin-destination (OD) data reported in the southern California OD survey for 3,217 traffic zones cover five counties, Los Angeles, Orange, Riverside, San Bernardino and Ventura. This OD data consists of six classes of OD matrices corresponding to trip types such as home-work, home-other, other-other, other-work, home-shop and truck trip. The definitions of these trip types are extracted from the survey below. The OD demands used to estimate highway network performance are based on the 3-hour trip ratios and corresponding average vehicle occupancy rates. (Shiraki, 2000 & 2007 and Zhou, 2006).

Home-work : Any trip where the origin or destination was HOME or WORKING-AT HOME, and the corresponding destination or origin was WORK or WORK-RELATED.

Home-other : Any trip where the origin or destination was HOME or WORKING AT HOME, and the corresponding destination or origin was not WORK, WORK-RELATED or SHOPPING.

Other-other : Any trip where the origin or destination and the corresponding destination or origin was PICK-UP, SCHOOL, SOCIAL, RECREATION, EAT OUT, PERSONAL or OTHER.

Other-work : Any trip where the origin or destination was WORK or WORK-RELATED and the corresponding destination or origin was not HOME, WORK or WORKING AT HOME.

Home-shop : Any trip where the origin or destination was HOME or WORKING AT HOME, and the corresponding destination or origin was SHOPPING.

Truck trip : TRUCK trip between any two locations.

The target area of this study is Los Angeles and Orange counties, so the area is different from the five counties covered by the OD survey. Therefore, the original OD data has to be converted to the node OD data for adjusting to this highway model and being the matrix size to computable. For doing this, the Thiessen function within the Arc/Info geographic information system (ArcGIS, 2009) was utilized, and the new OD data and zones were eventually aggregated to a 148 by 148 matrix. Also, the trip production and attraction of each trip types were condensed for use of trip reduction model. The specific processes of this aggregation technique are described in the previous research (Zhou, 2006).

2.6.2 Origin-destination data change after earthquake

Seismic damages to buildings reduce the travel demand until completion of rehabilitation work because the usage and function of damaged buildings are usually restricted and hindered for functional and safety reasons. For example, workers cannot work in the offices which suffered damages from earthquake at least for malfunction of electric power supply, and shoppers are unlikely to go earthquake damaged shopping centers for avoiding secondary damage. These kinds of damages cause a fall in travel demand. In addition, if the pre-earthquake travel demand (i.e., unreduced demand) is applied to the traffic analysis of seismic damaged highway network, the difference of estimated results (e.g., time and economic losses) between pre- and post-earthquake traffic analysis will be overestimated because of the lack of consideration for decreased trip demand. For dealing with these problems, in this methodology, the trip reduction model is incorporated to the highway traffic analysis for post-earthquake situation. The estimation of trip reduction phenomena is performed by identifying relationships between earthquake intensity and building damage (i.e., usable floor area) and converting the damage to change in activities (i.e., building population) and travel demands. The ratio of reduced building population to the baseline population is used to modify trip origins from or destinations to a given zone, and the reduction in trips for a given purpose reflects occupancy levels. Then, the vectors representing the number of post earthquake trips generated from and destined to a particular zone are obtained. The evaluated trip reduction rates corresponding to level of ground motion for all 6 trip types are shown in Table 2.3 and Figure 2.6-11 (Shinozuka et al., 2005 and Zhou, 2006).

Table 2.3 Person trip reduction rate corresponding to earthquake intensity.

Trip purposes		Level of ground motion				
		MMI6	MMI7	MMI8	MMI9	MMI10
		PGA=0.13g	PGA=0.27g	PGA=0.52g	PGA=0.93g	PGA=1.55g
Home-Work	Origin	0.032 (%)	0.260 (%)	0.743 (%)	5.537 (%)	14.441 (%)
	Destination	0.045 (%)	0.334 (%)	0.794 (%)	7.911 (%)	24.938 (%)
Home-Other	Origin	0.032 (%)	0.260 (%)	0.743 (%)	5.537 (%)	14.441 (%)
	Destination	0.043 (%)	0.329 (%)	0.769 (%)	7.422 (%)	23.548 (%)
Other-Other	Origin	0.043 (%)	0.326 (%)	0.765 (%)	7.339 (%)	23.246 (%)
	Destination	0.043 (%)	0.326 (%)	0.765 (%)	7.339 (%)	23.246 (%)
Other-Work	Origin	0.045 (%)	0.334 (%)	0.794 (%)	7.911 (%)	24.938 (%)
	Destination	0.043 (%)	0.329 (%)	0.769 (%)	7.422 (%)	23.548 (%)
Home-Shop	Origin	0.032 (%)	0.260 (%)	0.743 (%)	5.537 (%)	14.441 (%)
	Destination	0.036 (%)	0.294 (%)	0.651 (%)	6.243 (%)	20.185 (%)
Truck trip	Origin	0.035 (%)	0.369 (%)	0.889 (%)	8.783 (%)	25.191 (%)
	Destination	0.035 (%)	0.369 (%)	0.889 (%)	8.783 (%)	25.191 (%)

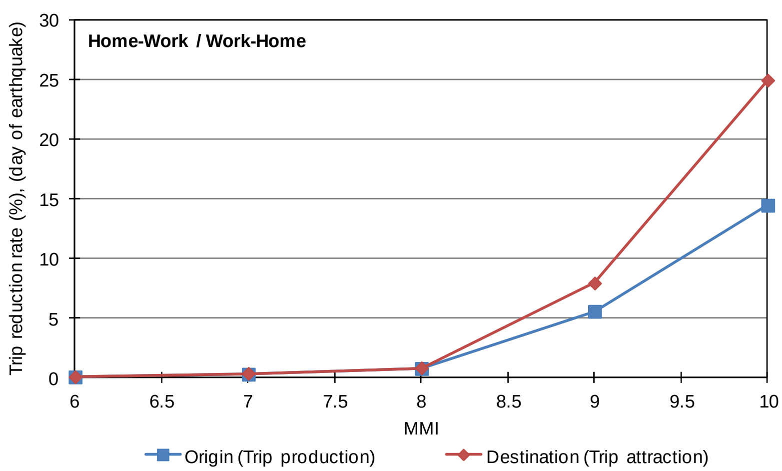


Figure 2.6 Trip reduction rate and earthquake intensity: home-work.

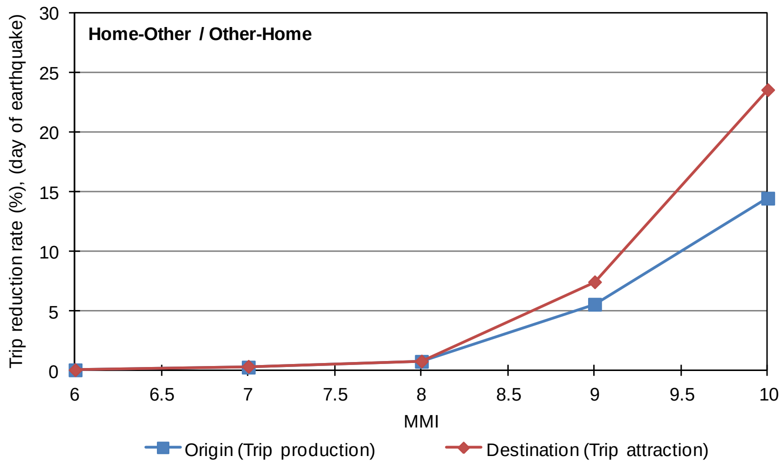


Figure 2.7 Trip reduction rate and earthquake intensity: home-other.

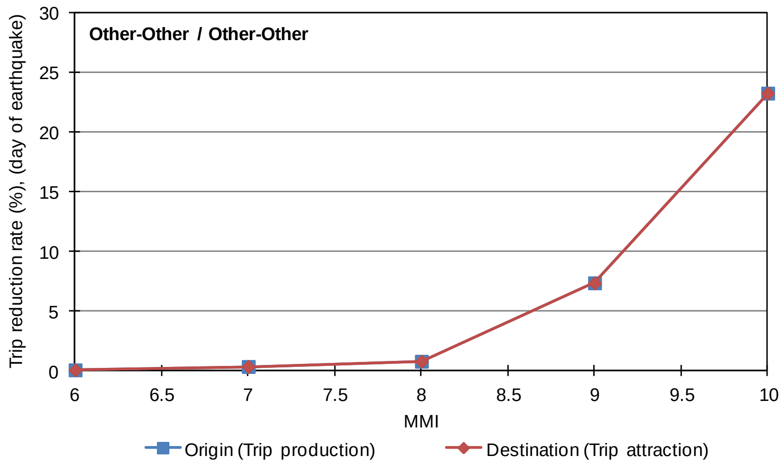


Figure 2.8 Trip reduction rate and earthquake intensity: other-other.

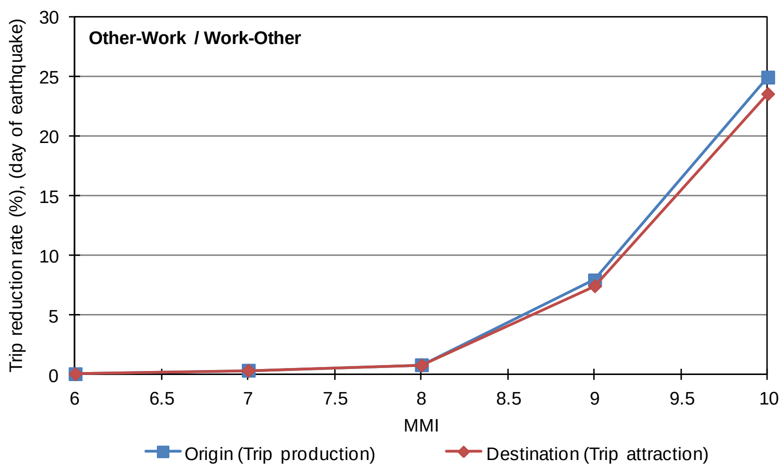


Figure 2.9 Trip reduction rate and earthquake intensity: other-work.

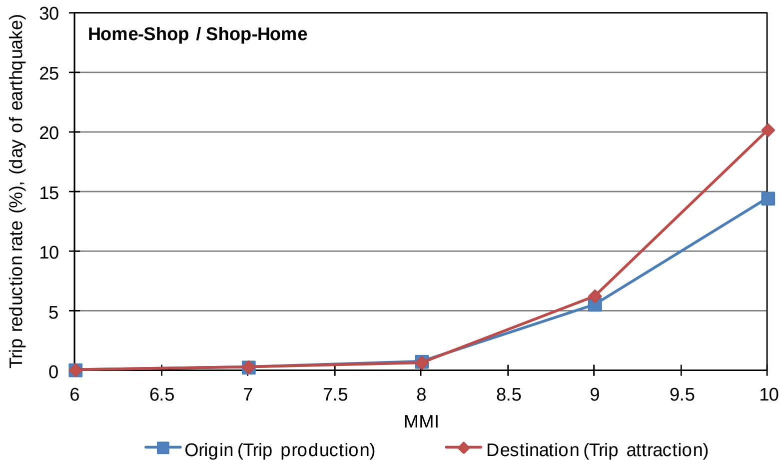


Figure 2.10 Trip reduction rate and earthquake intensity: home-shop.

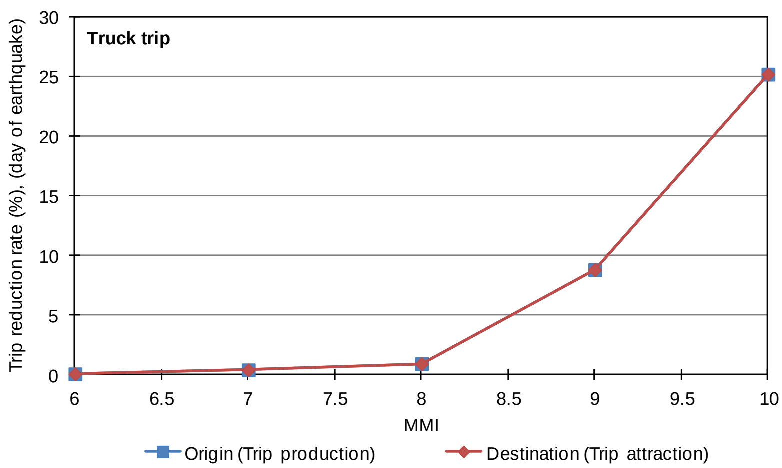


Figure 2.11 Trip reduction rate and earthquake intensity: truck trip.

2.6.3 Integrated traffic analysis

The estimated trip reduction is then integrated into the traffic analysis. This analysis method developed by a previous study (Shinozuka et al., 2005) produces post-earthquake traffic volumes (in passenger car unit, PCU), and estimates system-wide travel costs (i.e., hours) for the estimation of travel time loss. The reduction models adjust pre-earthquake trip production and attraction according to the reduction rates corresponding to earthquake intensity at the zones. A distribution model generates OD matrix for post-earthquake travel demand based on adjusted trip production and attraction and travel cost. A network assignment model then loads the travel demand in OD matrix onto the earthquake damaged network and estimates post-earthquake traffic volume and congested travel time. Figure 2.12 shows the flow of the integrated traffic analysis of trip reduction model and network models (Shinozuka et al., 2005).

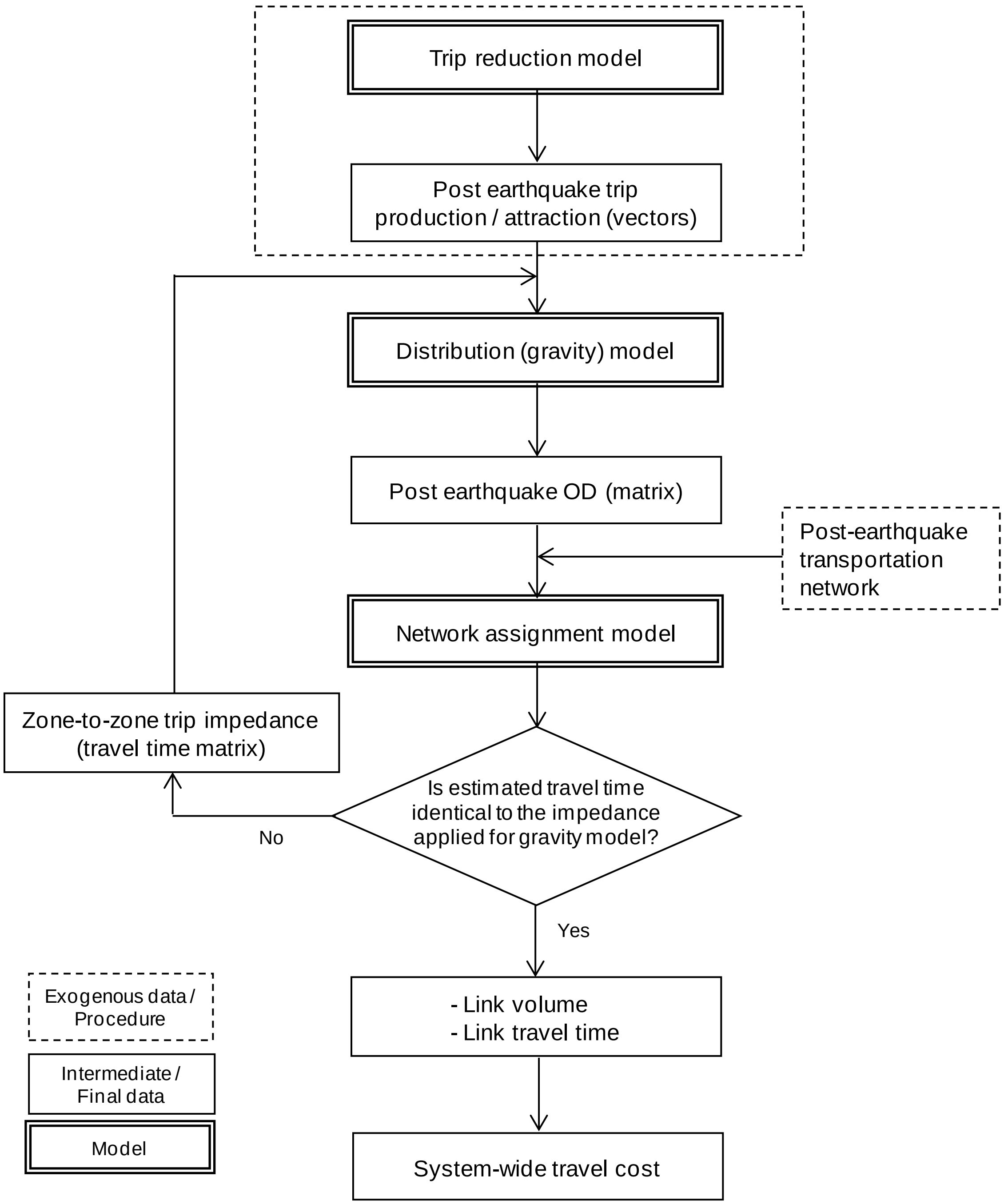


Figure 2.12 Integrated traffic analysis of trip reduction and network models.

More specifically, the post-earthquake trip attraction and production vectors should be converted to a demand matrix to ensure compatibility with transportation network model. To convert the estimated vectors into an OD matrix, a distribution model such as the gravity model is incorporated. The gravity model estimates travel demand in a matrix form in which rows represent origin zones and columns express destination zones. In this study, a doubly-constrained gravity model is applied, distributing post-earthquake travel demand based on two criteria, (1) travel demand between an origin-destination pair is proportional to the trips emanating from the origin zone and trips attracted to the destination zone and (2) the lesser the travel cost between a zone-pair, the more demand is allocated (distance-decay function). The network assignment model such as the user equilibrium model then assigns the estimated post-earthquake travel demand, represented by the OD matrix, to the most efficient routes between zones. The user equilibrium model adjusts link volume and congested travel time to achieve the equilibrium condition as shown in Figure 2.13 where travel times are identical for all routes based on Wardrop's 1st principle in this study. The total travel time spent by drivers at equilibrium (sum of travel time multiplied by the volume of the links in the network) represents the new system-wide travel cost, and its difference from original pre-earthquake baseline costs constitutes the seismically induced travel time loss (Shinozuka et al., 2005).

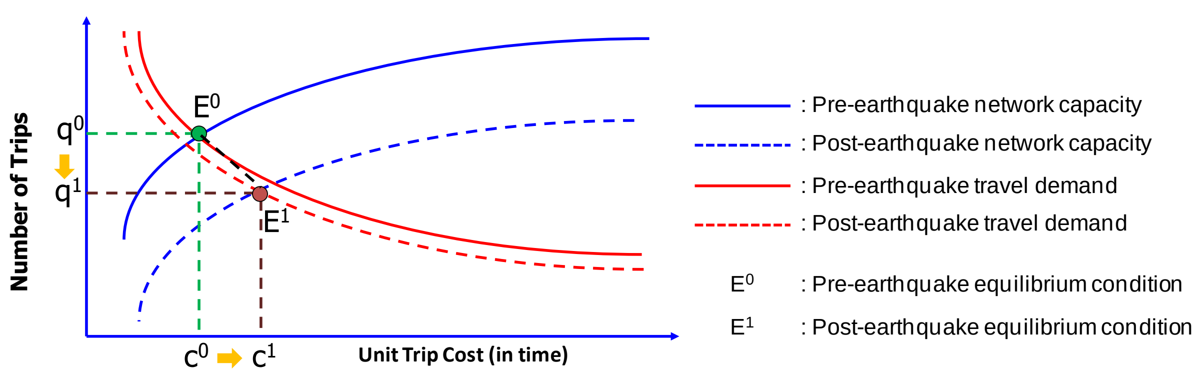


Figure 2.13 Equilibrium conditions on pre- and post-earthquake.

The integrated traffic analysis is conducted by following Evans formulation (1976) for combining the distribution model and network assignment model. It adjusts OD matrix and link volume simultaneously with application of two consecutive iterations such as the iterative secant method. The objective function of this non-linear optimization problem is expressed in Equation (2.4). The first term of the right-hand-side in this equation presents travel cost associated with user equilibrium assignment. The second term estimates costs associated with the travel distribution. Minimizing these costs corroborates the generation of link traffic volume x_a (and thus the travel cost by Equation (2.8)) and OD, t^p_{ij}. The trip reduction model and the distribution model are included in this integrated analysis as constraints. Equations (2.10) discount baseline trip production and attraction according to estimated reduction rates for each traffic analysis zones and trip purpose. Equation (2.9) depicts the distribution model using the gravity model. With successive average schemes, the iterative secant method is able to solve the system of

$$Z = \min Z(\mathbf{x},\mathbf{t}) = \sum_a \int_0^{x_a} c_a(w)dw + \sum_p \left(\frac{1}{\beta^p} \sum_i \sum_j t_{ij}^p \cdot \ln\left(t_{ij}^p\right) \right) \tag{2.4}$$

subject to

$$f_{ij}^{pk} \geq 0 \qquad \forall\, p,k,i,j \tag{2.5}$$

$$t_{ij}^p \geq 0 \qquad \forall\, p,i,j \tag{2.6}$$

$$\sum_k f_{ij}^{pk} = t_{ij}^p \qquad \forall\, p,i,j \tag{2.7}$$

$$x_a = \sum_p \sum_{i,j} \sum_k f_{ij}^{pk} \cdot \delta_{ij}^{a,k} \qquad \forall\, a \tag{2.8a}$$

$$c_{ij} = \sum_a c_a(x_a) \cdot \delta_{ij}^{a,k} \qquad \forall\, a \tag{2.8b}$$

$$t_{ij}^p = O_i^p \cdot D_j^p \cdot K_{ij}^p \cdot \exp\left(\alpha^p + \beta^p \cdot c_{ij}\right) \qquad \forall\, p,i,j \tag{2.9}$$

$$O_i^p = \mathbf{O}_i^p \left(1 - \xi_i^p\right) \tag{2.10a}$$

$$D_j^p = \mathbf{D}_j^p \left(1 - \varsigma_j^p\right) \tag{2.10b}$$

where

x_a = flow on link *a*;

t_{ij}^p = trip rate of type *p* between OD pair *i*-*j*;

f_{ij}^{pk} = flow of type *p* on path *k* connecting OD pair *i*-*j*;

c_{ij} = travel time between OD pair *i*-*j*;

c_a = link performance function of link *a*;

$\delta_{ij}^{p,k}$ = 1 if *a* is on path *k* between OD pair *i*-*j*, 0 otherwise;

O_i^p = trip generated from zone *i* for purpose *p*;

D_j^p = trip destined to zone *j* for purpose *p*;

$\mathbf{O}_i^p$ = baseline (pre-earthquake) trip generation from zone *i* for purpose *p*;

$\mathbf{D}_j^p$ = baseline (pre-earthquake) trip destination to zone *j* for purpose *p*;

ξ_i^p = trip reduction rate at zone *i* for production of purpose *p*;

ς_j^p = trip reduction rate at zone *j* for attraction of purpose *p*;

α^p, β^p = calibrated distance-decay coefficients for purpose *p*;

K_{ij}^p = calibrated balancing coefficients for purpose *p* ($K_{ij}^p = A_i \cdot B_j$);

A_i = balancing coefficient associated with origin zone *i*;

B_j = balancing coefficient associated with destination zone *j*;

p = trip purposes.

Equations from (2.4) to (2.10) through algorithm consisted of four steps. Step 0 is to initialize variables. OD and link volume are set 0, while c_{ij} is set to the travel time on minimum paths between zone-pairs based on free flow speed. The trip reduction model calculates post-earthquake trip attraction and production. Step 1 checks if the algorithm is running too many times, relative to M (iteration limit). If it is, the algorithm stops at this moment. Step 2 estimates OD using calibrated gravity model with travel time. The estimated OD only reflects travel time that was calculated in step 0, or step 4, and combined with that previously estimated by weighted average. The new OD is used in step 3 to generate link volume. Link volume is also combined with that generated by the previous iteration. Step 4 updates travel time. If travel times estimated from two consecutive iterations are not significantly different, the algorithm stops at this moment. Otherwise, step 1 to step 4 are repeated again (Shinozuka et al., 2005).

2.6.4 Travel demand recovery

As estimated in chapter 2.6.2, travel demand such as trip motivation decreases sharply right after earthquake happens because destination buildings like offices and shopping centers also suffer seismic damages. However, this OD change due to trip reduction is supposed to recover gradually from the worst level at the occurrence of earthquake as repair works for damaged buildings progress. This is because people also need to travel for working and shopping to throw themselves back into life as soon as the restoration is made. On the other hand, finding the correct rate of travel demand recovery is very difficult because many factors like reconstruction works, utility recoveries and societal situations are related to each other. Also, there are not any information regarding the relationship between demand recovery and these factors recorded at past earthquakes. Therefore, in this study, the travel demands of all 6 trip types are assumed to be linearly changed to the pre-earthquake level by taking certain time

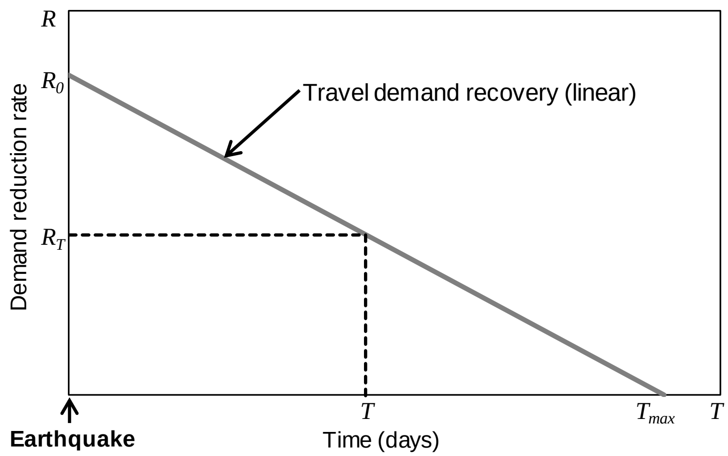


Figure 2.14 Travel demand recovery model.

depending on earthquake intensity at a corresponding zone. The linear recovery function shown in Figure 2.14 consists of time and travel demand reduction rate. The full recovery time, T_{max}, is modeled by the earthquake intensity at zone, Modified Mercalli Intensity scale (MMI), and the maximum term, 365 days (1 year). This function is expressed as follow:

$$T_{\max} = 365/(10 - g), \quad (days) \tag{2.11}$$

where g is the MMI scale at the zone, $g < 10$. Therefore, a shorter recovery period than 365 days is applied to a less intensive zone. The trip reduction rate, R_T, at an arbitrary time is assumed by the function of recovery time, T and T_{max}, as follow:

$$R_T = R_0(1 - T/T_{\max}) \tag{2.12}$$

where R_0 is the initial trip reduction rate estimated in chapter 2.6.2. The trip reduction rate is then continually improved by following these functions according to a certain recovery time (Shinozuka et al., 2005).

2.7 Social loss as highway performance

For representing performance degradation of highway transportation network, drivers' delay and trip opportunity loss are employed for scaling the increasing congestion and the reduction in opportunity, respectively. The summation of drivers' delay and opportunity loss is defined as total social loss induced by seismic damage of highway network. These losses are estimated by time unit, and each time losses are then converted to monetary unit through driver time value estimated by Caltrans.

2.7.1 Drivers' delay

The degraded road capacity causes additional driving time for fewer lanes, closed routes, less capacity detours and collapsed bridges. This kind of traffic congestion is gradually eliminated by the progress of road capacity recovery in highway network (i.e., system restoration). Therefore, drivers' delay is appropriate for expressing restoration process of highway performance. The drivers' delay, λ, is estimated as the difference of total drivers' travel time between the intact network and the degraded network. The drivers' delay can be calculated based on links shown in Equation (2.13a) as well as origin-and-destination pairs formulated by Equation (2.13b) (Shinozuka et al., 2005).

$$\lambda = \sum_a x_a^{'} t_a^{'}(x_a^{'}) - \sum_a x_a t_a(x_a) \quad (2.13a)$$

$$= \sum_i \sum_j \left(q_{ij}^{'p} \cdot c_{ij}^{'} - q_{ij}^{p} \cdot c_{ij} \right) \quad (2.13b)$$

where

x_a = flow on link *a* in intact network (pre-earthquake);

t_a = travel time on link *a* in intact network (pre-earthquake);

$x_a^{'}$ = flow on link *a* in damaged network (post-earthquake);

$t_a^{'}$ = travel time on link *a* in damaged network (post-earthquake);

q_{ij}^{p} = trips of type *p* from zone *i* to zone *j* in intact network (pre-earthquake);

c_{ij} = travel time zone *i* to zone *j* in intact network (pre-earthquake);

$q_{ij}^{'p}$ = trips of type *p* from zone *i* to zone *j* in damaged network (post-earthquake);

$c_{ij}^{'}$ = travel time zone *i* to zone *j* in damaged network (post-earthquake).

2.7.2 Opportunity loss

Trips are derived from various activities such as working and shopping. If drivers cannot make trips for any reasons, they also cannot perform those activities that originally cause the trips and undeniably have some value. This kind of cancellation of trips induces another type of loss called opportunity loss. Opportunity loss is represented by the product of the reduction of trip numbers and the rise of trip time as depicted in Figure 2.15. Opportunity loss is obviously improved by the recovery of highway function, so this is also adequate for using an index to represent highway performance level during reconstruction process. This kind of loss due to trip

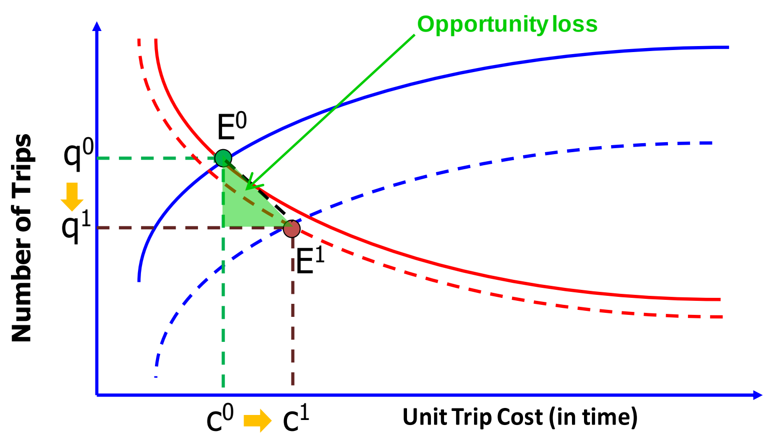


Figure 2.15 Conceptual illustration of trip opportunity loss.

cancellation should be counted in this study because traffic analysis considers travel demand reduction in post-earthquake circumstances. The opportunity loss of trip type p, ϕ_p, can be calculated as follow:

$$\phi^p = \sum_i \sum_j \left[\left(q_{ij}^p - q_{ij}^{'p} \right) \left(c_{ij}^{'} - c_{ij} \right) / 2 \right] \tag{2.14}$$

where

q_{ij}^p = trips of type p from zone i to zone j in intact network (pre-earthquake);

c_{ij} = travel time zone i to zone j in intact network (pre-earthquake);

$q_{ij}^{'p}$ = trips of type p from zone i to zone j in damaged network (post-earthquake);

$c_{ij}^{'}$ = travel time zone i to zone j in damaged network (post-earthquake).

Opportunity loss is calculated by trip purposes. In theory, link volume cannot be purpose-specific in node-based (or link-based) user equilibrium model. This is because there would be only one delay cost per model application. However, according to the systems of equations in Equations (2.4) through (2.10), demand (or OD) is estimated for individual trip types. Then, Equation (2.14) can be applied to each OD matrix, along with a common travel time matrix, c_{ij}. Consequently, the equation allows disaggregating the opportunity loss into different trip types (Shinozuka et al., 2005).

2.8 Business and non-business loss

Total social loss (i.e., the sum of drivers' delay and trip opportunity loss) due to seismic degradation of highway network performance is basically expressed as the sum of all 6 trip types cumulated during the entire restoration period in previous researches (Shinozuka et al., 2005 and

Zhou, 2006 & 2010). The disaggregation of this total social loss is sometimes necessary to provide the business-related loss for quantifying the total seismic economic loss for a record/information. This is because the economic value of business-related loss, in addition to time loss, is very important for managing regional economic activities from the standpoint of business field. Moreover, some researches in economic field divide travel cost due to seismic damage into some categories such as personal travel and freight travel, and they estimate each travel cost separately (Cho et al., 2001 and Gordon et al., 1998). In this study, total social loss is divided into two categories, business and non-business, according to trip types in order to dissect each type's transportation loss. The trips of home-work, other-work and truck are classified as business-related trips, and the trips of home-other, other-other and home-shop are sorted as non-business trips as shown in Figure 2.16. Then, those losses estimated by time unit are converted to monetary unit in basis on Caltrans' economic valuation about averaged unit cost of drivers' time. Caltrans' estimations used for this study are shown in the next page. Then, the impacts of business loss and non-business loss related to traffic damage can be separately scrutinized, and the disaggregated losses can be useful source for making decisions.

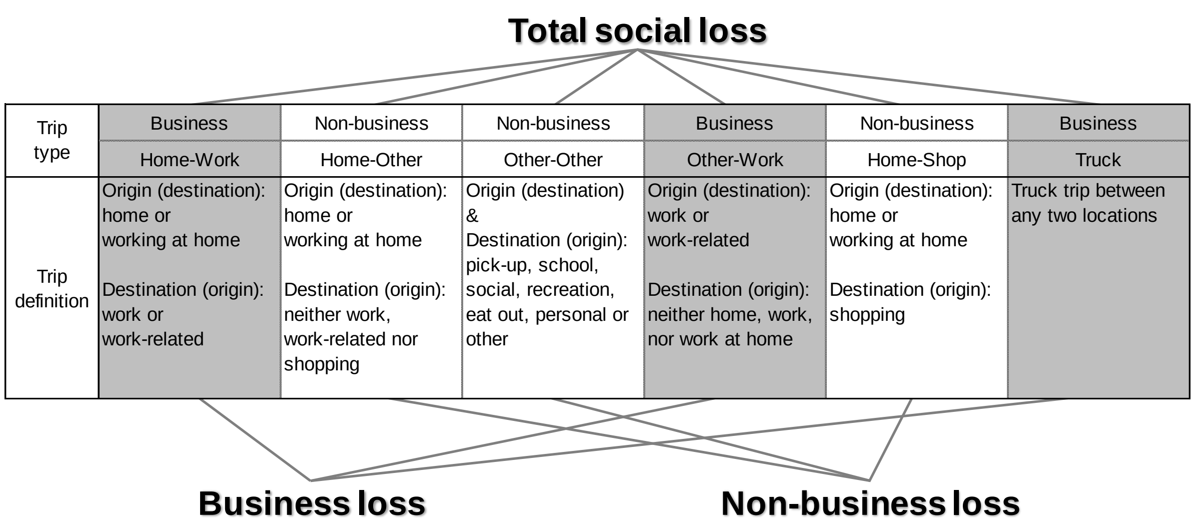


Figure 2.16 Business and non-business trips relating to highway transportation.

[Life-Cycle Benefit-Cost Analysis Economic Parameters 2012 by Caltrans]
(http://www.dot.ca.gov/hq/tpp/offices/eab/benefit_cost/LCBCA-economic_parameters.html)

Value of time	Dollars per person hours
Automobile	US$ 12.50
Truck	US$ 28.70
Auto/truck composite (weighted average)	US$ 17.35
Average vehicle occupancy rate	1.15

Furthermore, the bridge repair cost as direct loss definitely exists. The cost for repairing bridges physically changes depending on material price and labor cost at that time, so it cannot be decided explicitly. However, in this study, the bridge replacement cost is assumed to be US$ 196.30/ft^2 (per deck area, Caltrans 2012 estimation) and be proportional to the damage state (FEMA, 2003) for simplicity. The damage ratios recommended in HAZUS®MH MR4 technical manual (FEMA, 2003) are 0.00 for No damage, 0.03 for Minor, 0.08 for Moderate, 0.25 for Major and 1.00 for Collapse. Caltrans' estimated unit cost of bridge replacement is shown below.

[Construction statistics 2012, Division of engineering services, Caltrans]
(http://www.dot.ca.gov/hq/esc/estimates/Construction_Stats_2012.pdf)

Total amount (US$)	US$ 442,969,970.00
Total deck area (ft^2)	2,256,721.00 ft^2
Averaged unit amount (US$/$ft^2$)	196.30 (US$/$ft^2$)

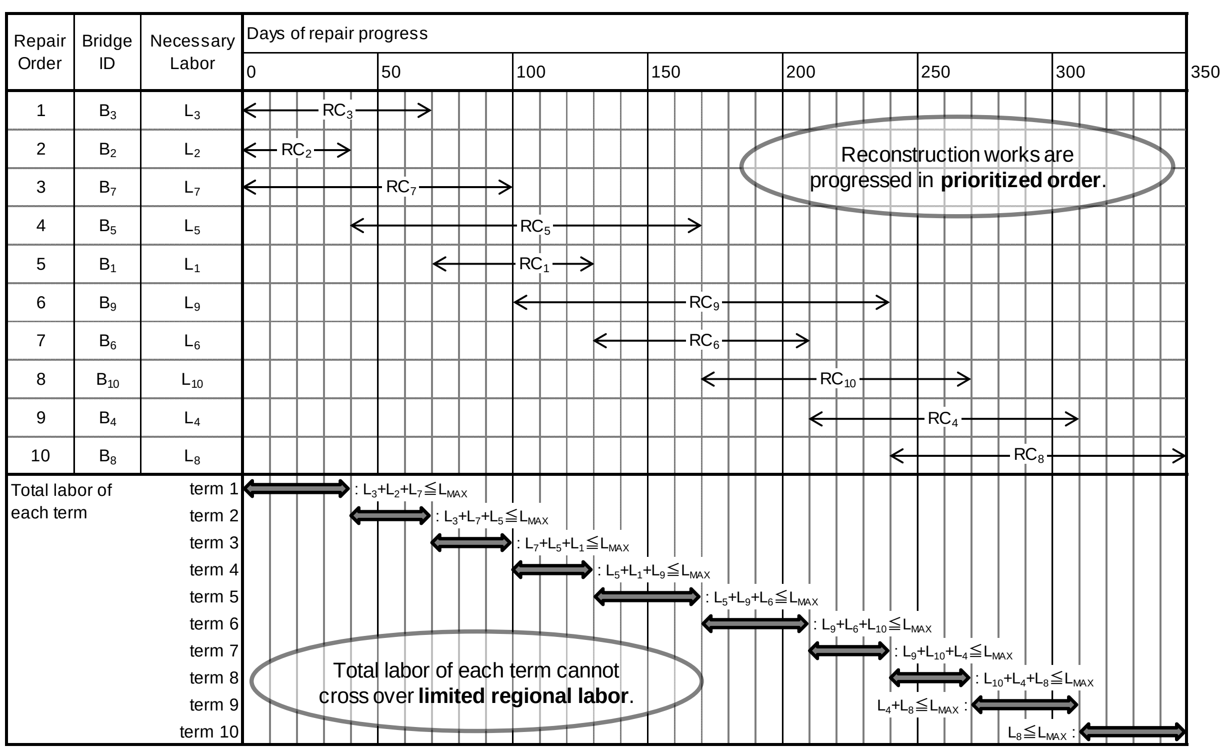
Chapter 3

Restoration process

As stated in chapter 1, the restoration works for disaster damages proceed through several stages. Firstly, the repair orders have to be decided after investigation of bridge damage status. Then, repair construction works are moved ahead along the orders decided on damage states with the ever-changing post-earthquake circumstance. In this study, Analytic Hierarchy Process (AHP) is employed to prioritize the repair orders based on several criteria associated with practical situations. This algorithm which can consider many criteria hierarchically and numerically is useful for the simulations on several repair scenarios and the comparison examination between those different passages for helping decision-making. In the reconstruction process of bridges, many uncertainties such as physical factors (e.g., material supply delay and equipment lack) and environmental factors (e.g., decision delay and additional inspection) exist. Those uncertainties significantly effect on the progress of reconstruction in a time manner. Markov Chain process model which is appropriate for reflecting the daily change of repair is used for simulating bridge reconstruction process probabilistically through Monte Carlo technique, and those uncertainties are assumed to be included into the established model by the calibration based on Northridge earthquake records because modeling those uncertain factors separately is complicated and difficult task at this moment. In addition, the progress of reconstruction work is constrained by a number of limited regional labor for simulating more realistic passage of construction work. This means that the repair work of all bridges cannot be started simultaneously right after earthquake like previous studies, but it is proceeded in the basis of limited number of available construction workers in the target region.

3.1 Repair progress concept

The reconstruction work is, in this study, postulated to progress based on the prioritized repair order and the constraint of limited regional labor with updating recovery status by bridge restoration model, and the conceptual figure of repair passage is shown in Figure 3.1. First, the repair orders are decided according to prioritization criteria. Then, the reconstruction work is simulated by the bridge restoration model under the condition of the total labor for repairing bridges in each term cannot cross over the limited regional labor. The time lag of reconstruction start date between bridges is considered in this concept. Here, the total labor is the accumulated necessary labor of bridge reconstruction, and the limited regional labor is the maximum workforce for highway construction in Los Angeles and Orange counties under post-earthquake situation. The reason for adopting the reconstruction labor rather than the repair cost is that the



* Necessary labor: Required construction workers for repairing bridges correponding to damage state and bridge deck area.
* Repair order: The order of repairing bridges based on prioritization estimated by AHP.
* L_{MAX}: Limited (maximum) regional labor for repairing bridges after earthquake.

Figure 3.1 Bridge reconstruction work progress based on repair order and limited labor.

construction workers are absolute necessary factor for bridge repair but the cost can be paid after completion in various ways. In Figure 3.1, for example, the repair work for bridge 5 cannot be started until the reconstruction of bridge 2 is completed, because there is not any extra labor in term 1 for the limited labor constraint. And, the completion date of bridge 2 is simulated stochastically based on Markov Chain process model as well as other bridges. On the other hand, the possibility that bridge 3 or bridge 7 completes before bridge 2 remains during term 1 in an extreme case, because it is evaluated probabilistically through simulations. Thus, the repair progress is simulated along this concept.

3.2 Repair prioritization

Repair prioritization for damaged bridges is one of the most important factors in post-earthquake restoration process because the repair order greatly effects on the total indirect loss of network function induced during the entire restoration period. Many related factors are complexly intertwined with each other in the decision-making process, and those factors are, for example, organization policy, route importance, urgency of a particular area, initial damage status, reconstruction difficulty and limited budget and/or labor. Although the decision-making process is so complicated, the judgment generally has to be made immediately for quick recovery, hazard elimination, emergency route securing and so forth. Therefore, conceivable sequences based on different reconstruction orders need to be prepared for supporting decision-making of repair prioritization before disasters, and their effectiveness for damage mitigation should be compared with each other based on a target criterion. As some previous researches tried to find the optimal retrofit order before earthquake on the basis of traffic interruption caused by seismic damage by following Northridge earthquake lessons (CSSC, 1994, SAB 1994, Na et al., 2008 and Sgaravato et al., 2008), and the best suited repair orders for damaged bridges after earthquake also need to be studied. The prioritizing algorithm, Analytic Hierarchy Process, applied to this study and several criteria for prioritizing orders are described in the following sections.

3.2.1 Analytic Hierarchy Process

Analytical Hierarchy Process which can consider many criteria hierarchically is applied to decide the priority of bridge repair order systematically (Saaty, 1980 & 1982). As its conceptual diagram is shown in Figure 3.2, proper criteria with respect to decision (i.e. repair order as 1st hierarchy) have to be extracted at first, and pairwise comparison between two alternatives (i.e., bridges as 3rd hierarchy) regarding each criterion (i.e., difficulty, importance, urgency and cost as 2nd hierarchy) is then conducted relatively for all combinations and criteria. Then, the amount of priority of each alternative is measured numerically by the expected value of priority considering weight factor between each criterion. A noteworthy advantage of this method is to be able to change weight between each criterion easily for adapting damage situation. Since the most important factor for prioritizing repair order changes depending on the situation of post-earthquake in each case, the repair prioritization needs to be adjusted for the

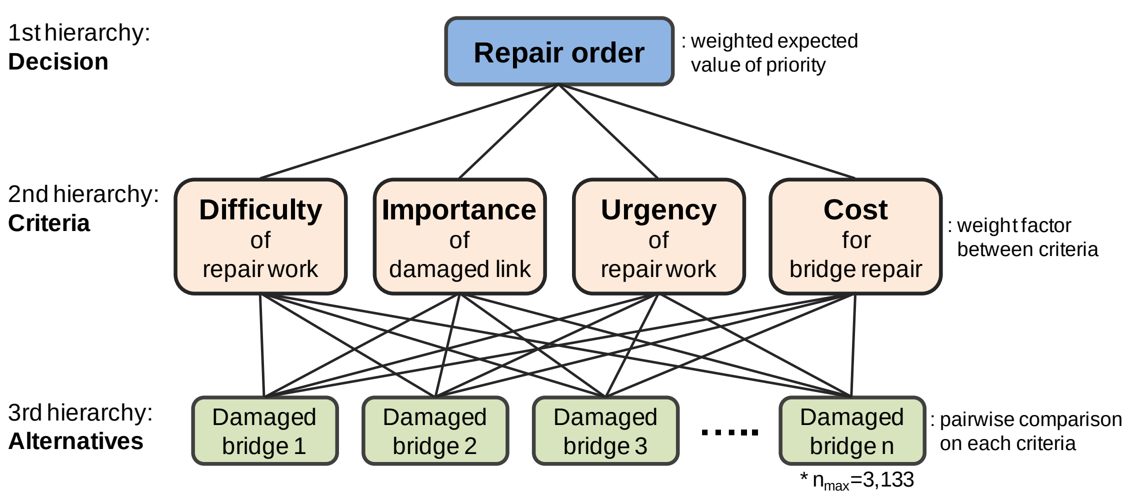


Figure 3.2 Conceptual figure of Analytical Hierarchy Process.

best recovery in the circumstance. In this sense, Analytic Hierarchy Process is a suitable method to help a systemized practical ordering. In fact, this process is applied to structure decision-making for periodical pavement maintenance by Virginia Department of Transportation (Larson et al., 2007).

The basic procedure of Analytic Hierarchy Process is explained by the following mathematical expressions (Saaty, 1980). The process briefly consists of four steps as follows: (1) Establish matrix of pariwise comparison about alternatives and criteria; (2) Calculate priority vector for all combinations; (3) Obtain priority value as weighted average from priority vectors; (4) Confirm the consistency of priority value. The pairwise comparison is denoted by ${}_k a_{ij}$ and ${}_k a_{ji}$ as follows:

$$\begin{aligned} &{}_k a_{ij} = {}_k w_i / {}_k w_j \,, \\ &{}_k a_{ji} = {}_k w_j / {}_k w_i \,, \qquad i,\ j = 1, \ldots, n \\ &{}_k a_{ij} = 1 / {}_k a_{ji} \end{aligned} \tag{3.1}$$

where ${}_k a_{ij}/{}_k a_{ji}$ is ijth/jith pairwaise comparison value of kth element (i.e., alternatives or criteria), ${}_k w_i/{}_k w_j$ is ith/jth weight value of kth element (i.e., relative weight between each component of kth element) and n is the total number of components of kth element. Clearly, a_{ij} indicates the strength of w_i compared with w_j. The matrix of pairwise comparison value of kth element is then denoted ${}_k A$ in the form of reciprocal as follow:

$${}_k A = \begin{bmatrix} 1 & {}_k a_{12} & \cdots & {}_k a_{1n} \\ 1/{}_k a_{12} & 1 & \cdots & {}_k a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/{}_k a_{1n} & 1/{}_k a_{2n} & \cdots & 1 \end{bmatrix} \tag{3.2}$$

where ${}_k A$ can be called consistent because $a_{il}=a_{ij}a_{jl}$ for all i, j, l. Then, this relationship can be converted as follows:

$$\sum_{j=1}^{n} {}_k a_{ij} \cdot {}_k w_j \big/ {}_k w_i = n \qquad i = 1, \ldots, n, \quad or$$
$$\sum_{j=1}^{n} {}_k a_{ij} \cdot {}_k w_j = n \cdot {}_k w_i \qquad i = 1, \ldots, n \tag{3.3}$$

which is equivalent to

$$_k A \cdot {}_k w = n \cdot {}_k w \tag{3.4}$$

where $_kw$ is an eigenvector of $_kA$ with eigenvalue n. And, if the diagonal of matrix $_kA$ consists of ones (i.e., $_ka_{ii}$=1), and if $_kA$ is consistent, then small variations of $_ka_{ij}$ keep the largest eigenvalue, $_k\lambda_{\max}$, close to n, and remaining eigenvalues close to 0 as follow:

$$_k A \cdot {}_k w = {}_k \lambda_{\max} \cdot {}_k w \tag{3.5}$$

where $_kw$ is the priority vector of kth element with largest eigenvalue $_k\lambda_{\max}$ (i.e., dominant eigenvector). Eventually, the priority values of all alternatives are obtained by multiplying matrices of criterion's priority vector and alternative's priority vector as follw:

$$_{CA_k} w = {}_C w \cdot {}_{A_k} w \tag{3.6}$$

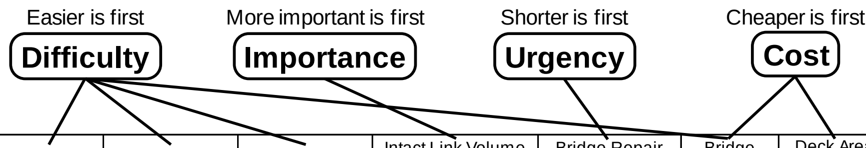
where $_{CAk}w$ is the final priority vector of kth alternatives considering criterion's priority, $_Cw$ is criterion's priority vector and $_{Ak}w$ is kth alternative's priority vector. Alternative which has larger priority value is then prioritized faster with respect to repair order. For confirming the consistency of priority value, the deviation of $_k\lambda_{max}$ from n is measured, and it can evaluate the closeness to consistency. Then, the consistency index, C.I., as expressed in Equation (3.7) is adopted, and the number should be generally less than 0.1 for the acceptable result.

$$\text{C.I.} = (\lambda_{\max} - n)/(n-1)$$
$$(or, \text{C.R.} = \text{C.I.}/\text{R.I.} \le 0.1, \text{R.I.}\,\textit{(random index)} = 1.59) \tag{3.7}$$

3.2.2 Prioritizing criteria

There are normally a lot of arguments to determine the priority of repair order, and it might be impossible to represent them explicitly in reality. However, some kinds of numerical expressions are needed for prioritization by the algorithm using Analytical Hierarchy Process, so this study attempts to quantify those resources of decision in numerical term based on several factors. First of all, difficulty of repair work, importance of damaged link, urgency of repair work and cost for bridge repair are adopted to prioritize repair order (i.e., prioritizing criteria) in this study. For difficulty criterion, the difficulty level of construction work is focused on, and the bridge with easier reconstruction will be prioritized first. The importance of highway road segment such as link volume is concentrated on for importance criterion, and the bridge in a link which has more traffic volume in ordinary time will be repaired first in importance criterion. The rapidity of bridge reconstruction completion is defined as urgency criterion, and the reconstruction of bridge which can be repaired in shorter period will be started first in urgency criterion. The less amount of repair cost is assigned the higher priority for cost criterion, and the bridge which can be rehabilitated at less cost will be given more priority in cost criterion. The weight values defined in the previous section between four criteria can be decided depending on the judgment of decision-maker. For example, the weight value of difficulty criterion is 1.0 and the others are 0.0 if the difficulty factor would be given the most priority. On the other hand, if all criteria would be assigned the priority evenly, the weight values of all criteria are equally 0.25. Thus, the weight between criteria can be designed according to various situations with no inhibition.

The weight values of all alternatives (i.e., damaged bridges in this case) for each criterion are calculated numerically by several factors as shown in Figure 3.3. Four factors are considered



Bridge ID	Span	Skew	Soil	Intact Link Volume (PCU): Round Trip	Bridge Repair Mean Time*	Bridge Damage*	Deck Area (ft^2)	Link ID
1	Multiple	0 - 20 (deg)	Soil A (Hard)	1670.35			600	1
2	Multiple	0 - 20 (deg)	Soil A (Hard)	1670.35			600	1
3	Multiple	0 - 20 (deg)	Soil A (Hard)	1670.35			800	1
4	Multiple	0 - 20 (deg)	Soil A (Hard)	1670.35			800	1
5	Multiple	0 - 20 (deg)	Soil A (Hard)	1670.35			781	1
6	Multiple	0 - 20 (deg)	Soil C (Soft)	1670.35			980	1
7	Multiple	0 - 20 (deg)	Soil C (Soft)	1670.35	Depending on earthquake		980	1
8	Multiple	0 - 20 (deg)	Soil C (Soft)	1670.35			1320	1
9	Multiple	0 - 20 (deg)	Soil C (Soft)	1670.35			1180	1
10	Multiple	0 - 20 (deg)	Soil C (Soft)	1670.35			828	1
11	Multiple	0 - 20 (deg)	Soil A (Hard)	1670.35			238	1
12	Multiple	0 - 20 (deg)	Soil C (Soft)	270.03			1296	2
13	Multiple	0 - 20 (deg)	Soil C (Soft)	270.03			1215	2
14	Multiple	0 - 20 (deg)	Soil C (Soft)	270.03			336	2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
3120	Multiple	0 - 20 (deg)	Soil C (Soft)	151349.73			1210	230
3121	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			3484	231
3122	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			3744	231
3123	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			2520	231
3124	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			1880	231
3125	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			2400	231
3126	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08	Depending on earthquake		2068	231
3127	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			2345	231
3128	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			3657	231
3129	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			2007	231
3130	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			3680	231
3131	Single	0 - 20 (deg)	Soil C (Soft)	79477.08			392	231
3132	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			588	231
3133	Multiple	0 - 20 (deg)	Soil C (Soft)	79477.08			2381	231

Figure 3.3 Weight values' factor of alternatives and criteria.

for the weight value of difficulty criterion, and they are postulated to be number of bridge span (single: 1 and multiple: 2), degree of bridge skew (0-20 deg: 1, 20-60 deg: 2 and larger than 60 deg: 3), soil condition at the site (hard soil: 1, medium soil: 2 and soft soil: 3) and bridge damage ratio (minor: 0.03, moderate: 0.08, major: 0.25 and collapse: 1.00). For importance criterion, the link volume (CPU) calculated on the intact traffic status is applied to the pairwise comparison of weight values. The average completion time assumed in the uniform distribution model for bridge restoration (Shinozuka et al, 2005) is adopted for the weight value of urgency criterion, and it corresponds to bridge damage state (minor: 80 days, moderate: 110 days, major: 155 days and collapse: 187.5 days). As the repair cost is presumed to be proportional to bridge damage state and deck area as stated in section 2.8, the weight value for cost criterion is decided by bridge damage ratio (minor: 0.03, moderate: 0.08, major: 0.25 and collapse: 1.00) and bridge deck area. Based on these weight values, the pariwise comparisons are conducted, and the matrices of pairwise comparison values are established.

3.3 Constrained repair conditions and calibration

The reconstruction work progress is constrained by the number of regional labor for bridge construction as stated in section 3.1 in this methodology. For this concept, the necessary labor for bridge construction (i.e., averaged unit labor) and the maximum number of regional labor in the aftermath of an earthquake need to be estimated. Both of them are statistically derived from the records regarding bridge construction productivity, labor force survey, reconstruction work situation at post-earthquake and so forth. In addition, a calibration analysis for obtaining more accurate maximum regional labor is conducted by using Northridge earthquake records because the number of construction workforce in an earthquake damage area is supposed to be decreased for their seismic damages like transportation problem and/or residence loss.

3.3.1 Necessary labor for bridge construction

Firstly, the averaged unit labor for bridge construction is applied to the necessary labor for bridge reconstruction work with consideration of post-earthquake work situation in this study. The averaged unit labor is estimated on the basis of several documents reported by Bureau of Labor Statistics (BLS, 1973, 1975, 1979, 1981a, 1981b, 1982 & 2003), Caltrans (U.S. DOT & ITS, 2002) and Ministry of Land, Infrastructure, Transport and Tourism, Japan (MILT, 1997, 2000, 2003, 2006, 2009, 2010 & 2011). Since the information about unit labor for civil structure construction in the U.S. is not available, this eventual needed value is evaluated by the relative comparison of the construction productivities of buildings and civil structures between the U.S. and Japan. As shown in the next page, the relative proportion of the averaged unit labor for building construction between the U.S. and Japan (i.e., 8.0/19.85) is assumed to be applicable to the ratio of the averaged unit labor for civil structure construction, and the unit labor for civil structure construction in the U.S. is then obtained as 7.9 (employees-day/year/10m^2) by calculating from the unit labor in Japan, 19.58 (employees-day/year/10m^2). And, the number of unit labor of the U.S. converted to daily and feet unit, 0.000308 (employees-day/ft^2), is consistent with the averaged unit number of workers for Akashi-Kaikyo bridge construction in Japan, 0.000529 (employees-day/ft^2). Next, some adjustment factors are considered to make this unit labor fit to the post-earthquake reconstruction circumstance such as more workers than usual. Those adjustment factors come from Northridge reconstruction records and an assumption. In the document originally reported by Caltrans (U.S. DOT & ITS, 2002), the highway repair work for Interstate 10 at Northridge earthquake was made under the condition of rush work such as 24-hour work days & 7 days a week (12 hour shifts), work on all weather conditions, 2 superintendents per project, 228 carpenters (normally 65), 134 iron workers (normally 15), accelerated material manufacturing and delivery, use early strength cure concrete, decision making and inspection 24-hours a day and so forth. In addition, it is assumed that two workers,

[Estimation of necessary labor for bridge construction]

BLS[*1] productivity (buildings) — 8.0 (employees-day/year/10m^2)
MILT[*2] productivity (buildings) — 19.85 (employees-day/year/10m^2)
MILT productivity (civil structures) — 19.58 (employees-day/year/10m^2)

Productivity (civil structures) estimation → 7.9 (employees-day/year/10m^2)
= 0.000308 (employees-day/ft^2)

considering conditions (adjustment factor)
mentioned in the above text and Caltrans report[*3] ⇨

<u>Necessary labor at post-earthquake reconstruction</u> → <u>0.095238 (employees-day/ft^2)</u>

*1: Bureau of Labor Statistics, United States Department of Labor
*2: Ministry of Land, Infrastructure, Transport and Tourism, Japan
*3: U.S. Department of Transportation and ITS Joint Program Office. (2002)

at least, need to work for reconstruction project of a collapsed bridge in this study. With consideration of adjustment factors based on urgent work mentioned above, the necessary unit number of bridge reconstruction labor is assessed as 0.095238 (employees-day/ft2). Then, the necessary labor for each bridge is calculated corresponding to assumed reconstruction labor rates (minor: 0.05, moderate: 0.10, major: 0.30 and collapse: 1.00) and bridge deck area.

3.3.2 Limited regional labor after earthquake

The number of maximum regional available labor for highway construction in Los Angeles and Orange counties is constantly in fluid for areal and temporal factors like regional economic condition and investment in road network. Since there are not any systematic data which specifically record the number of workers for highway construction in this area, the estimation of maximum workforce is also conducted by the relative comparison based on Caltrans report of skilled construction labor in 2008 (Caltrans, 2008a, 2008b & 2008c) and Bureau of Labor Statistics survey of regional and state employment and unemployment in 2013 (BLS, 2013) in this study. Total construction labor in California is assumed to change linearly from 2008 to 2013, and the change ratio is gotten as the proportion of total labor in 2013, 616,500 (BLS, 2013), to that in 2008, 458,693 (Caltrans, 2008a), as indicated in the next page. The change ratio is used to calculate the specific number of highway construction workers in Los Angeles and Orange counties. This kind of total workers' number in 2008 is 4,770 based on Caltrans' recorded information. This number is then converted to 6,412 for the labor in 2013 by multiplying the change ratio, 1.344, because the clear record about the number of highway construction workforces in 2013 does not exist. However, the total number, 6,412, is just under the normal time (not the post-earthquake situation), so this number should be adapted to be more suitable number for reflecting seismic damage circumstance. The prediction of total number of

[Estimation of maximum regional labor in normal time]

Caltrans[*1] construction labor in California, 2008	458,693 (workers)
Caltrans[*1] highway construction labor in California, 2008	19,968 (workers)
Caltrans[*1] highway construction labor in LA, 2008	3,004 (workers)
Caltrans[*1] highway construction labor in OC, 2008	1,766 (workers)
BLS[*2] state construction labor in California, 2013	616,500 (workers)
Highway construction labor estimation in California, 2013	26,838 (workers)
Highway construction labor estimation in LA, 2013	4,038 (workers)
Highway construction labor estimation in OC, 2013	2,374 (workers)
Maximum regional labor in LA &OC in normal time	6,412 (workers)

*1: California Department of Transportation
*2: Bureau of Labor Statistics, United States Department of Labor

highway construction labor in a certain area, Los Angeles and Orange counties, is very difficult because there are a lot of factors which affect workforce trend. For example, workers might not be able to come to construction sites for traffic interruption caused by earthquake, workers may suffer serious seismic damage of themselves, their families and/or their properties, workers may not be able to receive job offers for a disruption of information-communication network due to earthquake and so on. Therefore, in this study, the total available highway construction labor after earthquake occurrence (most likely less than 6,412) is estimated by a calibration study based on the records of Northridge earthquake and the baseline labor number, 6,412. This calibration study and the final number of labor in this region are particularly described in the following section.

3.3.3 Calibration of regional labor

The daily passage of post-earthquake traffic volume record at four collapsed routes due to Northridge earthquake shown in Figure 3.4 is used for the calibration analysis of limited regional

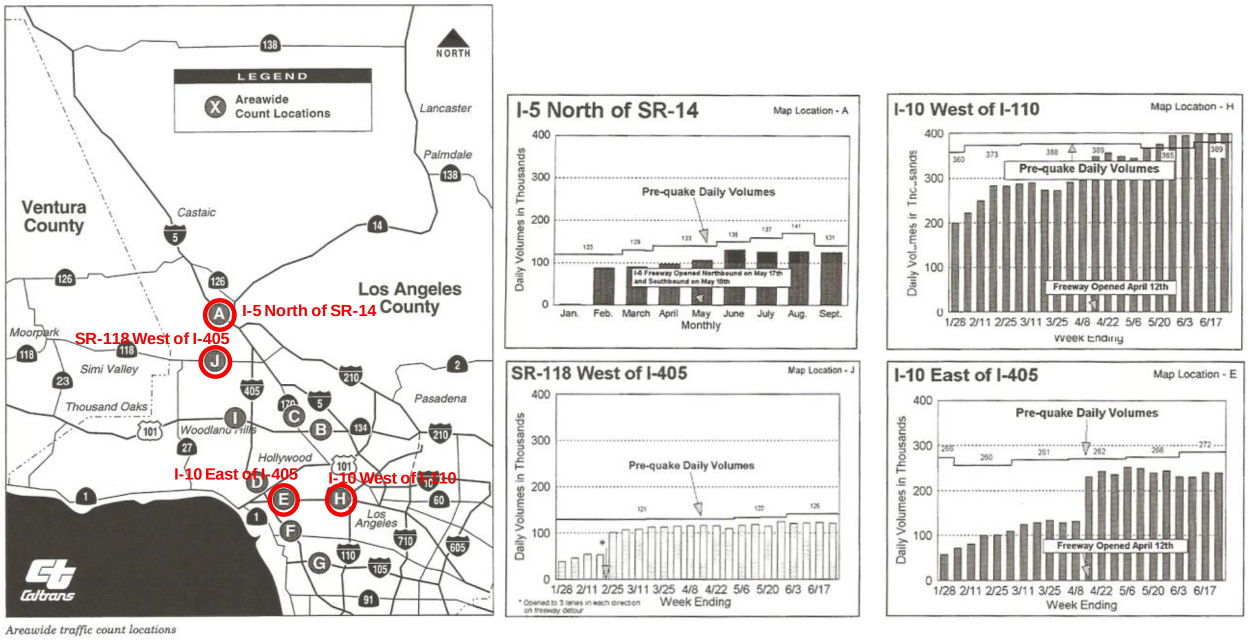


Figure 3.4 Traffic volume decline records and locations of four severe damaged routes at Northridge earthquake (Caltrans, 1995).

labor. The calibration is carried out through the traffic volume recovery comparison between this actual recovery passage based on Northridge records and the recovery curve simulated by established methodology with changing the number of limited labor. Then, the number of labor with the minimum error between both recovery curves is identified as the limited (i.e., maximum) regional labor for highway reconstruction under post-earthquake situation.

As shown in the declined traffic volume records in Figure 3.4, the actual daily reduction rates are calculated with the degraded volume and the pre-earthquake volume for four routes, I-5 North of SR-14, SR-118 West of I-405, I-10 West of I-110 and I-10 East of I-405. The four recovery curves in right-hand side of Figure 3.5 show the time passage of restored traffic volume of those routes, respectively, and the red line represents the averaged recovery curves of four routes. The left-hand side of the figure puts all recovery curves into the same time table. Here, the coefficient of variation (C.O.V) of four curves is calculated at all time steps, and the C.O.Vs until day 100, 0.10-0.36, are relatively large as compared to the C.O.Vs after day 100, 0.02-0.09.

This is thought to be due to the large dispersions caused by unstable situations during the initial term of entire post-earthquake period from day 0 to full-recovery such as confused vehicle trips or tangled traffic information. Also, the insufficient number of data is a possible cause of this trend. Hence, the comparison of traffic volume recovery curves in this calibration analysis is performed within the range of small dispersion.

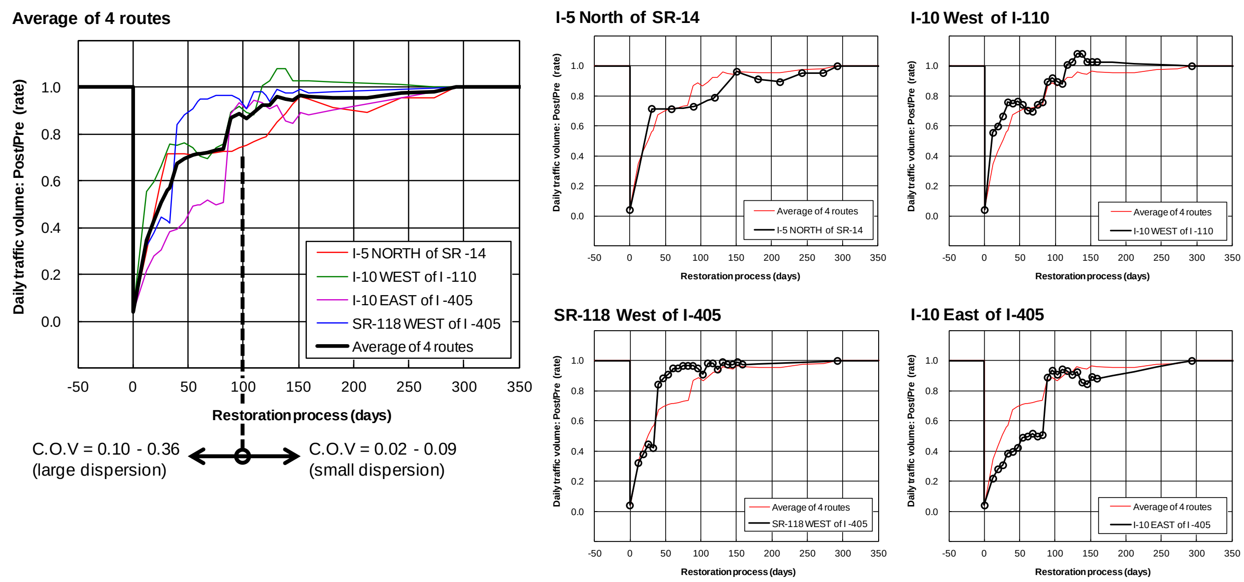


Figure 3.5 Traffic volume recovery curves based on Northridge earthquake records.

The simulated recovery curve of four routes is estimated by the developed highway network model. The Markov Chain process model proposed in section 3.4 is applied to bridge restoration model, the moderate residual traffic capacity is adopted for traffic network analysis, and the importance criterion is used for prioritizing repair order based on the descriptions of actual orders in several documents. Since the calibration is based on the actual damage due to Northridge earthquake, the actual damage of bridges and links and the Northridge earthquake intensity are also applied to the model. 9 bridges and 5 links (10 links as round trip) of the model corresponding to the four collapsed routes shown in Figure 3.4 are extracted in Table 3.1, and the intact traffic volumes of these links are then estimated by the model for the evaluation of

Table 3.1 Bridge, link and traffic volume of highway network model corresponding to Northridge earthquake severe damaged routes.

Route	Transportation Network Model		
	Bridge ID	Link ID	Intact Traffic Volume (PCU)
I-5 North of SR-14	1465, 1466	116, 347	45802.38
	1483, 1484	118, 349	75690.96
I-10 West of I-110 & I-10 East of I-405	713, 714	44, 275	253343.33
	741	45, 276	267439.54
SR-118 West of I-405	118, 120	9, 240	90170.60

traffic recovery rate. The traffic recovery curve of the corresponding links (i.e., routes) in the case of Northridge earthquake is then simulated through traffic network analysis and obtained by extracting from entire analyzed results of all links. The initial number of maximum labor is set as 6,000 based on the statistical estimation, 6,412, for calibration study, and the number of labor is gradually decreased to minimize the area difference (i.e., error) of recovery curves between the averaged Northridge record and the simulation results.

The results of calibration study and the identified limited regional labor are shown in Figure 3.6. The black line represents the averaged traffic recovery curves based on actual Northridge earthquake records, and the colored lines express the simulated recovery passages of traffic volume of the corresponding links. The calibration is conducted manually between 6,000 labors to 1,000 labors, and the each error within the range of small dispersion is shown in the graphs in right-hand side. The simulated processes of traffic recovery in the first figure are distinctly different each other, but the obvious difference cannot be seen from the calibration results in the second figure, especially between 2,700 labors and 3,200 labors. The smallest error is then obtained by the recovery curve derived from 3,000 labors. Therefore, the number of limited regional labor for highway reconstruction in Los Angeles and Orange counties under post-earthquake situation is identified as 3,000 by this calibration study. In addition, the common trends of recovery curve such as the steeper restoration in the beginning of repair term and the gradual restoration in the later part of reconstruction period can be found in the both recovery curves. From this standpoint of the recovery curve shape, the identified number of labor, 3,000, is considered appropriate for the limited regional labor.

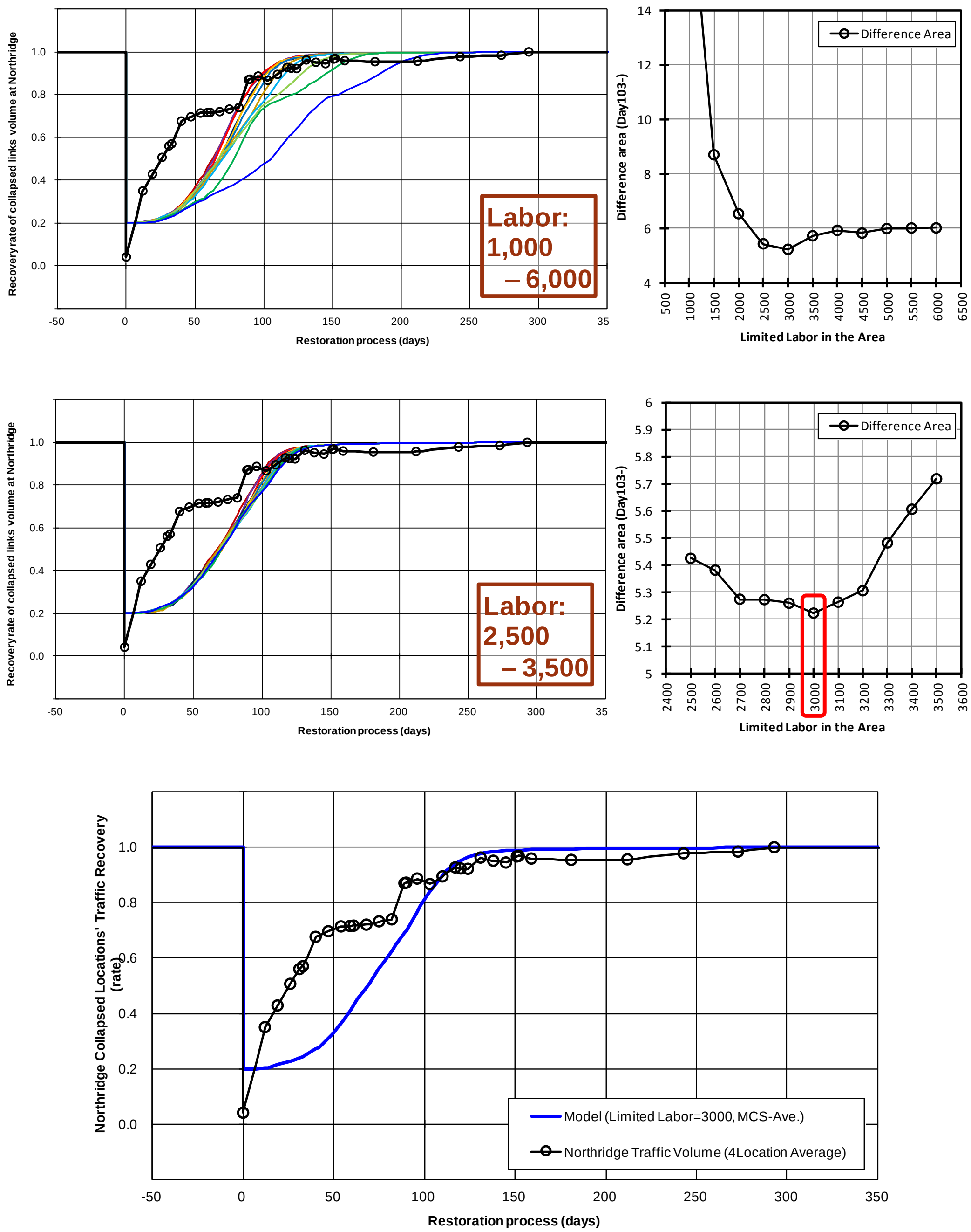


Figure 3.6 Calibrated result of regional limited labor in Los Angeles and Orange counties.

3.4 Bridge restoration process and calibration

Bridge restoration process should be evaluated probabilistically based on a stochastic model for considering several uncertainties mentioned in the beginning of this chapter because chronological records and information of those uncertainties about bridge repair activities were not documented very much at past disastrous earthquakes. Therefore, this study proposes to apply Markov Chain process model in addition to the existing models, Uniform distribution model and Normal distribution model, to simulate the bridge reconstruction process. This stochastic model, Markov Chain process, can update the probability to transit damage status (i.e., repair progress) depending on specific time step, and the transition probability matrix is identified based on the actual records of bridge repair progress at Northridge earthquake through calibration analysis. Bridge restoration progress is then simulated probabilistically based on the developed stochastic model through Monte Carlo technique (Hoshiya & Ishii, 1986).

3.4.1 Markov Chain process model

Uncertain events are more likely to be consisted of conditions changing spatially and temporally. For instance, those are temporal deterioration of concrete structures, spatially and temporal occurrence of earthquakes and hurricanes, temporal outbreak of accidents and so forth. Random changes of those conditions depending on changes of time and space should be expressed probabilistically based on stochastic processes. The bridge restoration process is one of those uncertain cases governed by temporal changes, and its condition at a certain time is supposed to depend on a condition at previous time (i.e., non-invertible). Then, in this study, the bridge restoration process is assumed that a future damage status (i.e., repaired damage state) only depends on the current status and is independent from the past status. The stochastic process with this probabilistic character is called Markov process and has several models such as

Poisson process, Markov Chain process, Binominal process, Random walk and Birth-death process. The basic expressions of Markov property can be described as follow (Ang & Tang, 1984 and Cox, 1965):

$$p(t+1) = P\left[X(t+1) \mid X(t)\right] \tag{3.8}$$

where $P[\cdot]$ is a probability of a condition, $X(\cdot)$ is a condition at a certain time and $p(t+1)$ is a conditional transition probability from the condition of $X(t+1)$ to the condition of $X(t)$. Thus, the probability of $X(t+1)$ is decided only by the probability of $X(t)$ at time t, one time step before $(t+1)$. In addition, the process is defined as Markov Chain process if the transition probability for one step is a certain probability without relying on time passage (i.e., time homogeneous). The Markov Chain process is then generally represented as follows in a form of vector:

$$\{X_{t+n}\} = \{X_t\}[P]^n$$

$$[P] = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \tag{3.9}$$

where $\{X_{t+n}\}$ is the state probability vector at nth time step t, $\{X_t\}$ is the initial state probability vector and $[P]$ is the transition probability matrix. Therefore, a temporal transition of state probability can be obtained specifically if an initial state probability and a transition probability are given. In this study, the Markov Chain process is used to model the bridge restoration progress. Since actual progress of reconstruction works changes depending on temporal advance and repaired status at the time, Markov Chain process is appropriate to simulate the restoration process in time domain. This is also because this process can renew a probability of damage rehabilitation/repair completion along a specific time step. Indeed, several researches adopt this process for analyzing restoration process (Cagnan & Davidson, 2004, Kozin & Zhou, 1990, Miles & Chang, 2004, 2008 & 2011, Zhang, 1992, Yamada et al., 1992 and Hoshiya & Koike, 1981). The extreme state probability vector at $n \to \infty$ converges with a certain probability called an absorbing state. And, the converged state probability at $n \to \infty$ is 1.0 in the case of treating a restoration process because the extreme state in this case is completely repaired (i.e., no damage).

For applying Markov Chain process to bridge restoration process, some assumptions are introduced in this study. Firstly, the initial state probability (i.e., the probability of initial bridge damage state) vector is decided explicitly based on the deterministic identification of bridge damage state as described in section 2.3. Secondly, the transition probability to improve from one damage state to the next damage state (e.g., from collapse to major or from moderate to minor) is assumed to be same for all damage state, and the transition probability means a probability which is staying at the present state or shifting to the next state. Thirdly, the damage state does not turn back to the worse damage state (i.e., non-decreasing process) because a repair process does not progress to any worse damage states in reality. Lastly, the time step of Markov Chain process model for bridge restoration is defined as 1 week (i.e., 7 days). The conceptual diagram of Markov Chain process model in this study is then depicted in Figure 3.7. The

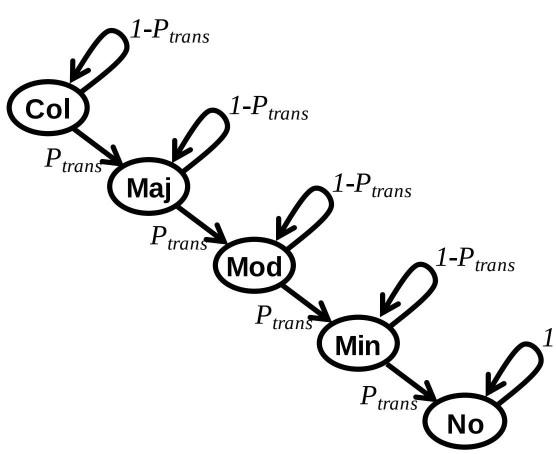


Figure 3.7 Schematic representation of bridge restoration model by Markov Chain process.

particular expressions of the initial state probability vector and the transition probability matrix can be represented as follows:

[Initial state probability vector]

$$\{X_t\} = \begin{array}{rl} & \begin{array}{ccccc} Col & Maj & Mod & Min & No \end{array} \\ Collapse & :\{ \begin{array}{ccccc} 1, & 0, & 0, & 0, & 0 \end{array} \} \\ Major & :\{ \begin{array}{ccccc} 0, & 1, & 0, & 0, & 0 \end{array} \} \\ Moderate & :\{ \begin{array}{ccccc} 0, & 0, & 1, & 0, & 0 \end{array} \} \\ Minor & :\{ \begin{array}{ccccc} 0, & 0, & 0, & 1, & 0 \end{array} \} \\ No\ damage & :\{ \begin{array}{ccccc} 0, & 0, & 0, & 0, & 1 \end{array} \} \end{array} \tag{3.10}$$

[Transition probability matrix]

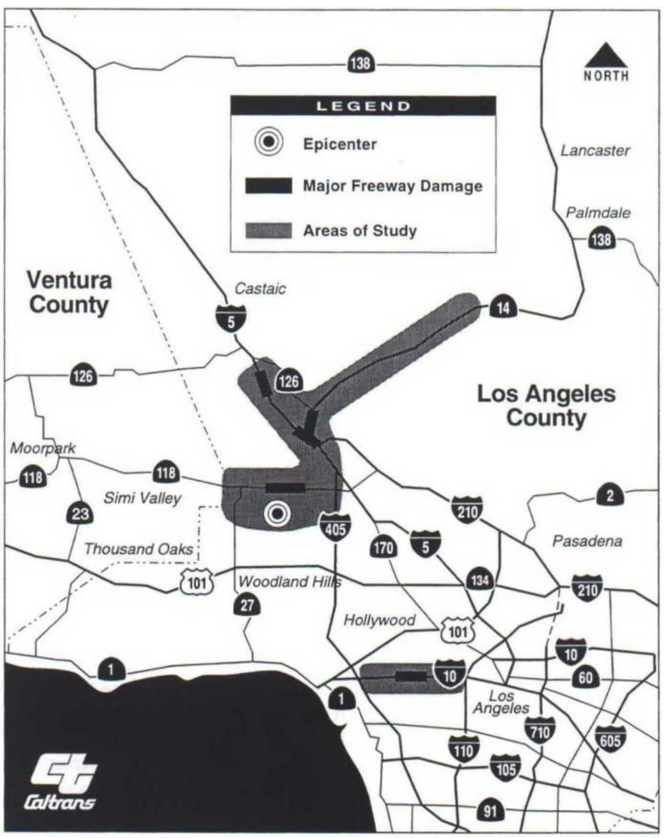
$$[P] = \begin{array}{c} \\ Col \\ Maj \\ Mod \\ Min \\ No \end{array} \begin{array}{c} \begin{array}{ccccc} Col & Maj & Mod & Min & No \end{array} \\ \begin{bmatrix} 1-P_{trans} & P_{trans} & 0 & 0 & 0 \\ 0 & 1-P_{trans} & P_{trans} & 0 & 0 \\ 0 & 0 & 1-P_{trans} & P_{trans} & 0 \\ 0 & 0 & 0 & 1-P_{trans} & P_{trans} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array} \tag{3.11}$$

where P_{trans} is transition probability. The transition probability is then estimated in the next section 3.4.2 based on the records at Northridge earthquake.

3.4.2 Calibration of transition probability matrix

The transition probability of Markov Chain process is normally estimated by an observed statistical data about time transition of an objective event. Therefore, if the event is, for example, a deterioration phenomenon of structure, a data of deterioration passage can be collected as time passage and accuracy of transition probability will be improved. However, in the case of restoration process after earthquake, it is very difficult to gather enough data of reconstruction progress because the event of disastrous earthquake is very rare and the sample size of reconstruction data is therefore very small. On the other hand, there are also some proposed mathematical equations for estimating one-step transition probability of Markov Chain process

(Kozin & Zhou, 1990 and Zhang, 1992,) with restriction of component size. In this study, a statistical calibration method is used to estimate the transition probability of Markov Chain process model based on bridge reconstruction records at Northridge earthquake. The severe damaged routes of highway network at Northridge earthquake and the chronological records of 9 collapsed bridges' reconstruction work are shown in Figure 3.8 (U.S. DOT & ITS, 2002 and Caltrans, 1995). The calibration is conducted through the bridge recovery rate comparison between the actual bridge recovery curve of these 9 collapsed bridges and the simulated bridge recovery process by Markov Chain process algorithm with adjusting several transition probabilities. Then, the transition probability with the minimum error between both bridge recoveries is identified as the most suited transition probability for post-earthquake bridge



Location of damage and areas of study

(Caltrans 1995)

Chronology of Events

Day 2 January 18, 1994	All I-5 lanes completely shut down between Roxford Street and north to Lyons Avenue in Santa Clarita; I-5 trucks-only lanes were undamaged and remain open. All SR-14 Lanes were closed. Local streets used as detours. All I-10 lanes closed between Centinela and Washington Blvd. Local streets used. All SR-118 lanes closed between Tampa Avenue and I-210. Local streets used. FEMA Special Facility Tele-registration Center is activated.
Day 5—Friday, January 21, 1994	I-10 northbound and southbound connectors to I-405 were opened.
Day 9—Tuesday, January 25, 1994	Metrolink ridership hit 22,000 boardings per day, (normal average: 1,000 per day) along the new extension of the Santa Clarita rail line serving areas surrounding earthquake-damaged roads.
Day 12—Friday, January 28, 1994	The southbound SR-14 to southbound I-5 truck bypass opened with one HOV and one mixed-flow lane. I-5 detour route was opened using a reconstructed frontage road.
End of January	Lane capacity in the damaged roadway corridors is restored to 70 percent of the pre-earthquake level.
Early February	Regular system of detours and emergency express bus service are in operation.
Day 20—February 5, 1994	Construction on I-10 Santa Monica Freeway begins. Construction on Camarillo Metrolink begins.
Day 36 February 21, 1994	Westbound SR-118 was reconstructed and restriped to provide three eastbound and three westbound lanes, replacing the detours on local streets.
Day 85 April 11, 1994	I-10 Santa Monica Freeway opens 74 days ahead of schedule.
Day 121—May 17, 1994	I-5 Golden State Freeway at Gavin Canyon opens.
Day 173—July 8, 1994	The I-5/SR-14 Interchange re-opened 3 weeks ahead of schedule (2 ramps at the SR-14/I-5 Interchange re-open: southbound SR-14-southbound I-5 and northbound SR-14-northbound I-5).
Day 230 September 3, 1994	SR-118 Simi Valley Freeway westbound lanes opened more than 2 weeks ahead of schedule.
Day 234 September 7, 1994	September 7, 1994- eastbound SR-118 lanes re-open to traffic.
Day 293 November 4, 1994	The remaining two ramps at SR-14/I-5 interchange opened to traffic (southbound SR-14-northbound 1-5 and southbound I-5-northbound SR-14).

(U.S. DOT & ITS 2002)

Figure 3.8 Repair records and locations of nine collapsed bridges at Northridge earthquake (U.S. DOT & ITS, 2002 and Caltrans, 1995).

restoration progress. Since the number of actual data is small as mentioned before, a framework for collecting data regarding post-earthquake progress needs to be established for making the transition probability more accurate for future disasters.

The detailed chronological description of reconstruction works are shown in Table 3.2. Severe damaged locations are 4 such as I-5, I-5/SR-14, I-10 and SR-118, and each location has 1 to 3 collapsed bridges (Caltrans, 1994b, 1994c & 1995). Since start date and total period of all reconstruction works are completely different each other as shown in the table, the start date of all bridge repair works are replaced to Day 0 (i.e., day of earthquake) for the calibration purpose. Then, the bridge recovery curve based on Northridge records is established under the assumption that all construction works progresses simultaneously. In Table 3.3, the estimated chronological bridge restoration rate and the corresponding restored date are indicated. The recovery curve based on this table is depicted for expressing the restoration passage of 9 collapsed bridges at Northridge earthquake in Figure 3.9. The detailed information between start date and completion date was not collected at that time, so the process during the beginning of restoration

Table 3.2 The reconstruction records of 9 collapsed bridges at Northridge earthquake.

Rte.	I-5	I-5/SR-14 Interchange	I-5/SR-14 Interchange	I-10	SR-118	SR-118
Location	the bridge at Gavin Canyon.	"N/B SR-14 to N/B I-5connector" & "S/B SR-14 to S/B I-5 connector" bridges.	"S/B SR-14 to the N/B I-5 connector" & "S/B I-5 to N/B SR-14 connector" bridges.	the bridge at Fairfax Avenue and Washington Boulevard. the bridge at La Cienegae Boulevard and Venice Boulevard.	the bridge at Bull Creek. the bridge at Gothic Avenue and Mission.	the bridge at Gothic Avenue and Bull Creek. the bridge at Gothic Avenue and Mission.
Number of collapsed bridges	2	1	1	3	1	1
Damage	Collapse (rebuild)	Collapse (rebuild)	Collapse (rebuild)	Collapse (rebuild)	Collapse (rebuild)	Collapse (rebuild)
Demolition/Shoring	from Jan. 18 to Jan. 29 (11 days' construction).	from Feb. 11 to Mar. 17 (34 days' construction).	from Feb. 11 to Mar. 17 (34 days' construction).	N/A	N/A	from Jan. 18 to Feb. 21 (35 days' construction).
Rebuild/Repair	to May 18 (97 days' construction).	from Mar. 19 to Jul. 8 (112 days' construction).	from Jul. 9 to Nov. 4 (119 days' construction).	from Feb. 5 to Apr. 11 (66 days' construction).	E/B from Feb. 10 to May 13 (92 days' construction).	W/B from late May to Sep. 3 (110 days' construction).
Total days	108	146	153	66	92	145

period, from Day 0 to Day 66, cannot be estimated sufficiently and it is represented by linear passage. However, other proposed restoration models (Deco et al., 2013) state that the recovery process in the initial period transitions gradually and slowly. Therefore, the comparison of bridge recovery curves in this calibration analysis is performed between Day 66 and completion date in this study.

Table 3.3 Bridge restoration rate of 9 collapsed bridges at Northridge earthquake.

Route	Collapsed Bridge Number	Total Restoration Time (days)	Bridge Restoration (rate)	
			Each	Accumurate
I-10	3	66	0.333	0.333
SR-118	1	92	0.111	0.444
I-5	2	108	0.222	0.667
SR-118	1	145	0.111	0.778
I-5/SR-14 Interchange	1	146	0.111	0.889
I-5/SR-14 Interchange	1	153	0.111	1.000

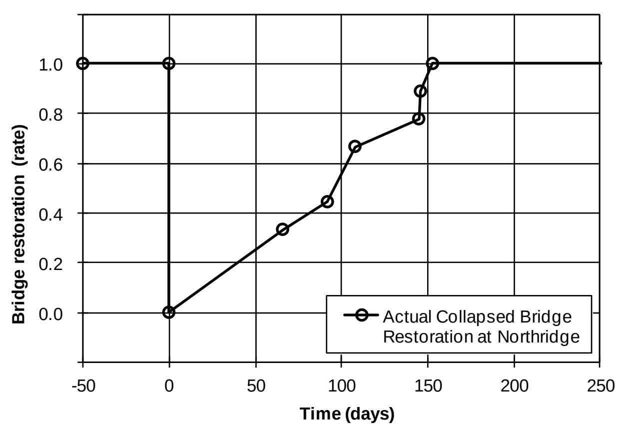


Figure 3.9 Bridge restoration curve of 9 collapsed bridges at Northridge earthquake.

The simulated bridge restoration curve of 9 collapsed bridges is evaluated by the bridge restoration algorithm using Markov Chain process. Since the established recovery curve at

Northridge earthquake is based on the simultaneous reconstruction work, the simulation is also conducted under the condition of coincidental repair work of all 9 bridges for this calibration purpose by setting regional limited labor unlimited. The same 9 bridges are considered as collapsed bridges for the simulation and are same as the bridges used for limited regional labor calibration shown in Table 3.1. Also, the Northridge earthquake intensity is applied to the algorithm. Then, the combination of transition probability and staying probability is properly changed to minimize the area difference (i.e., error) of recovery curves between the Northridge record and the simulation results.

The results of calibration study and the identified transition probability are shown in Figure 3.10. The black line represents the bridge recovery curves based on actual Northridge earthquake records, and the colored lines express the simulated bridge repair passages. The first calibration study is done manually by using transition probability between 0.10 and 0.20 (i.e., staying probability between 0.90 and 0.80) as shown in the first figures in Figure 3.10. The each error calculated between Day 66 to completion date is shown in the graphs in right-hand side. The recovery process estimated by larger transition probability is obviously faster than that using smaller transition probability, and the smallest error between actual record and simulated result is recognized from the simulation made by transition probability 0.16. Next, the second study is made within the range of transition probability between 0.138 and 0.178 (i.e., staying probability between 0.862 and 0.822) around the most suitable transition probability, 0.16, gotten from the first study. The smallest error is then obtained by the recovery curve derived from transition probability 0.158 and staying probability 0.842. Therefore, the combination of transition probability and staying probability for Markov Chain process model is identified as (0.158, 0.842) by the second calibration study. As shown in the third graph of Figure 3.10, the bridge recovery curves of Northridge earthquake records and the simulated curves on calibrated transition probability are quite matched except for the beginning period (i.e., between Day 0 and Day 66). In this sense, as stated before, the transition probability is supposed to be more precise if the calibration work will be conducted based on more data about bridge repair work, so it

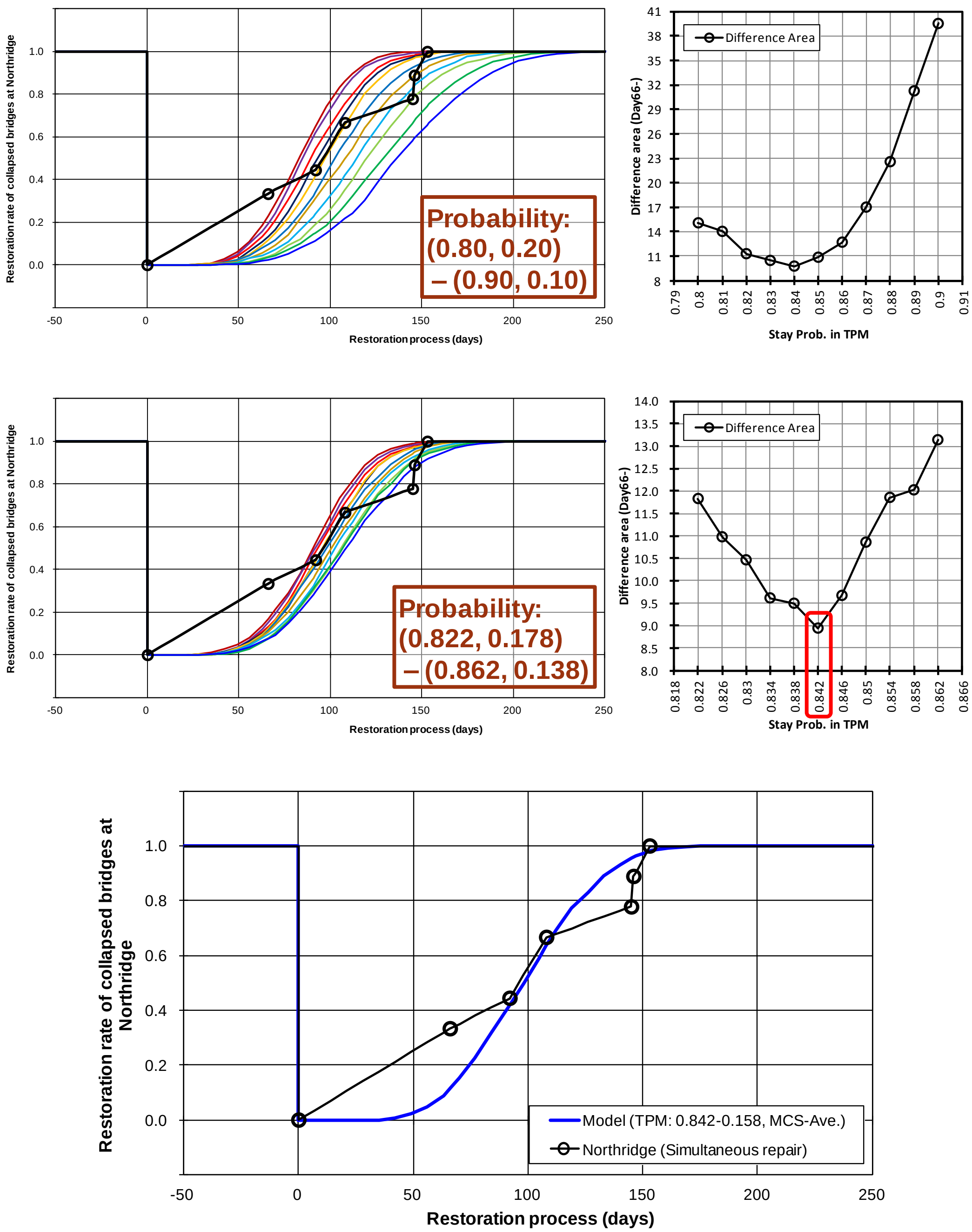


Figure 3.10 Calibrated result of Markov Chain process model for bridge restoration.

should be collected in a purposeful manner in the future.

The obtained transition probability is expressed in the form of matrix, $[P]$, consisting of all damage states in Table 3.4. The state probability distribution functions of Markov Chain

Table 3.4 Calibrated transition probability matrix of Markov Chain process model.

	Col	Maj	Mod	Min	No
Col	0.842	0.158	0	0	0
Maj	0	0.842	0.158	0	0
Mod	0	0	0.842	0.158	0
Min	0	0	0	0.842	0.158
No	0	0	0	0	1

process model based on this transition probability matrix are illustrated in all damage states, collapse, major, moderate and minor, in Figure 3.11. As shown in the figures, it doesn't always transfer to no damage (repair completion) from the initial damage state directly. In other words, for example, collapsed bridge might be restored in a step-by-step manner like collapse, major, moderate, minor and finally no damage. Therefore, this Markov Chain process model can reflect practical reconstruction progress by this distinctive character. In addition, as described in section 3.4.1, the state probability converges to 1.0 (i.e., no damage state) as time passes because bridge damage will be fully restored, eventually.

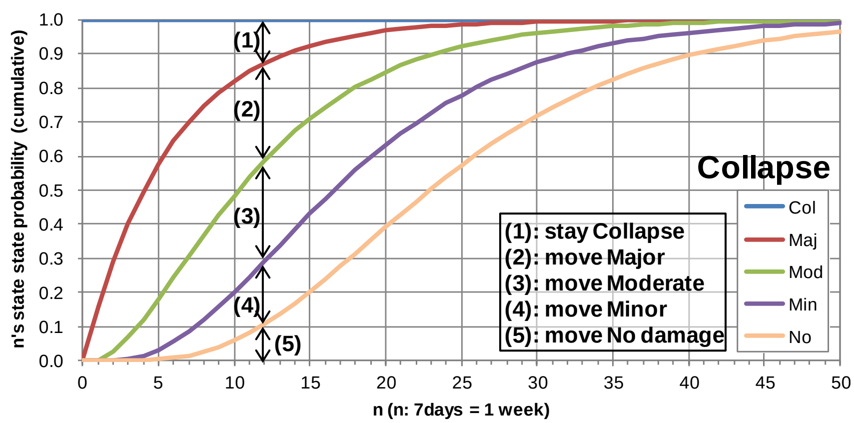


Figure 3.11 Markov Chain process model for bridge restoration.

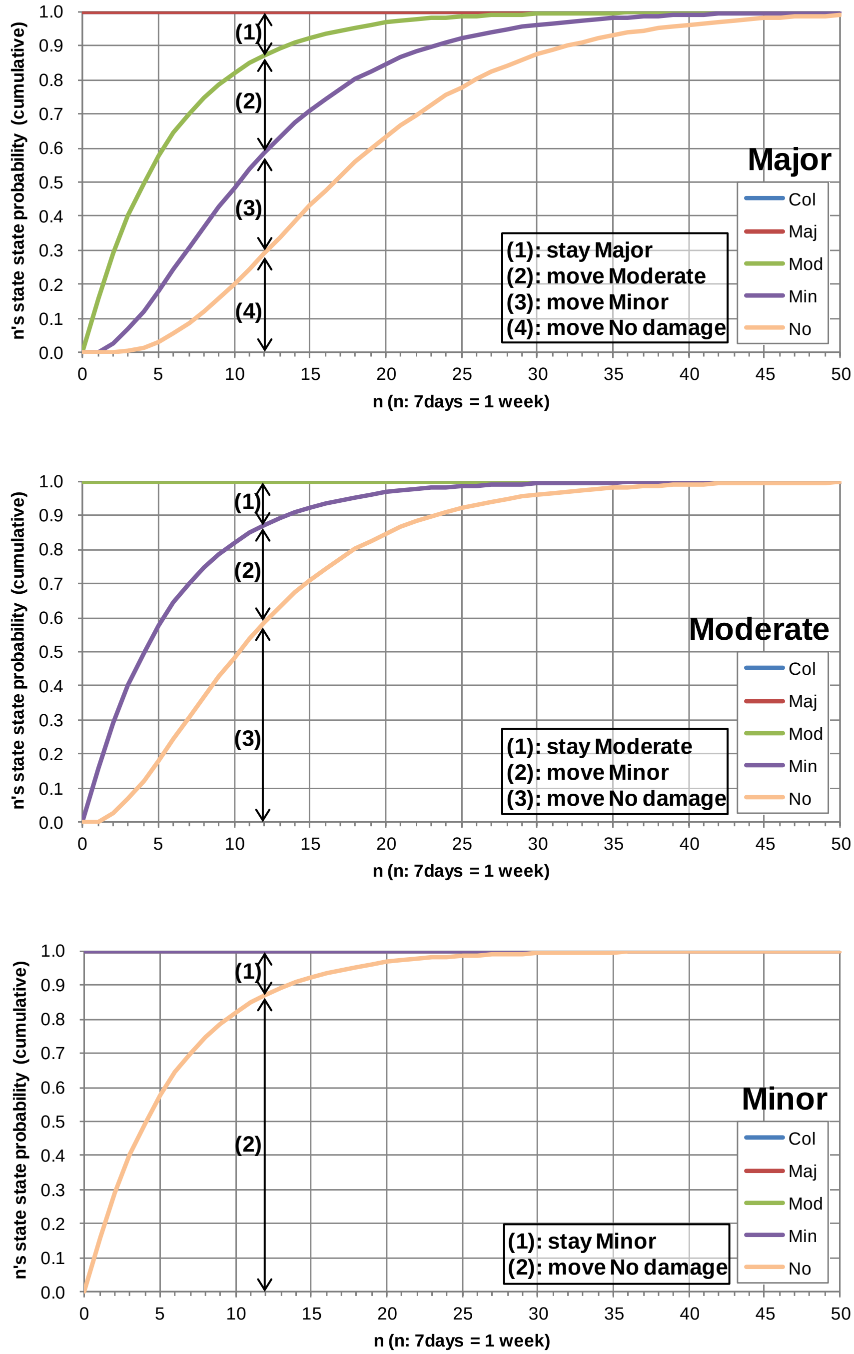


Figure 3.11 Markov Chain process model for bridge restoration (continued).

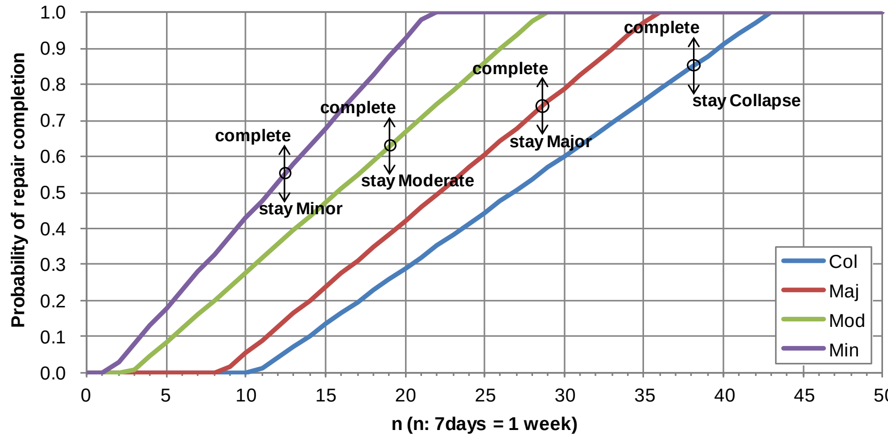
3.4.3 Uniform and Normal distribution model

There are several bridge restoration models proposed by previous researches (e.g., Shinozuka et al, 2005, FEMA, 2003, Mackie et al. and Deco et al., 2013). In this study, the uniform distribution model and the normal distribution model are applied to simulate bridge restoration progress for a comparative discussion with Markov Chain process model developed here.

The uniform distribution model is originally developed by Shinozuka et al. (2005) and is applied to represent the process for recovering bridge damage. In this model, the minimum time and the maximum time to complete repair work are postulated, and the repair completion probabilities are assumed to distribute uniformly between these optimistically and pessimistically times. For example, a bridge repair work could be completed evenly between Day 10 and Day 150 if the minimum time and maximum time are hypothesized as 10 days and 150 days, respectively. The repair progress is therefore evaluated probabilistically between the minimum and maximum time. On the other hand, the probability of repair completion is 0 before the assumed minimum time and is 1 after the postulated maximum time, so bridge restoration process is deterministically decided during these two terms. The mathematical expression of this model is shown as follows:

$$F(x) = \begin{cases} 0 & , \quad x \le \alpha \\ (x-\alpha)/(\beta-\alpha) & , \in [\alpha, \beta] \\ 1 & , \quad \beta \le x \end{cases} \tag{3.12}$$

where $F(\cdot)$ is probability distribution function of uniform distribution, x is time, α is the minimum completion time corresponding to damage state and β is the maximum completion time corresponding to damage state. And, probability distribution functions and characteristic values of uniform distribution model according to bridge damage status are illustrated in Figure 3.12. As indicated in the figure, bridge damage state is improved directly from initial damage state to no damage state (i.e., repair completion status), and this improvement is then reflected to the damage status of link and the traffic capacity of link in which the bridge locates.



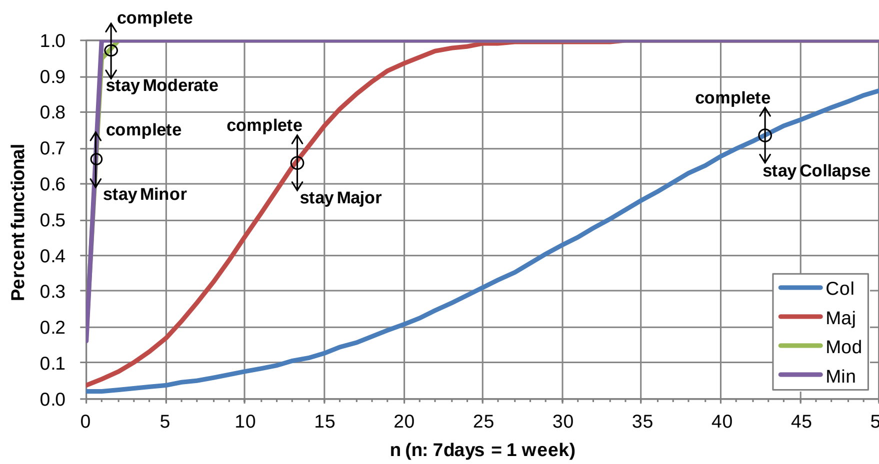
Damage state	Days for repair completion	
	Minimum	Maximum
Minor	10	150
Moderate	20	200
Major	60	250
Collapse	75	300

Figure 3.12 Uniform distribution model for bridge restoration (Shinozuka et al., 2003).

The normal distribution model is proposed as a bridge functionality restoration process in HAZUS®MH MR4 technical manual (FEMA, 2003). In this study, this bridge functionality progress is considered as a bridge recovery progress, and this normal distribution concept is then applied to simulate bridge reconstruction process. Therefore, the probability of bridge repair completion is assumed to be found along this probability distribution, and the model is established for all four bridge damage states such as minor, moderate, extensive (i.e., major) and complete (i.e., collapse). Contrarily, as shown in Figure 3.13, the mean values and standard deviations for minor and moderate damage are very small, the completion probabilities of the bridges suffered these damages are therefore decided in the almost deterministic stochastic field. The mathematical expression of this normal distribution model is represented as follow:

$$F(x) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma} \right)^2 \right] dx \qquad (3.13)$$

where $F(\cdot)$ is probability distribution function of normal distribution, x is time, μ is mean completion time corresponding to damage state and σ is standard deviation corresponding to damage state. And, probability distribution functions and main descriptors of normal distribution model according to bridge damage status are illustrated in Figure 3.13. As indicated in the figure and same as uniform distribution model, bridge damage state is improved directly from initial damage state to no damage state (i.e., repair completion status), and the bridge is then modified possessing full performance in highway network from the next date which means that this improvement is reflected to the damage status of link immediately.



Damage state	Main descriptor (days)	
	Mean	S.D.
Minor	0.6	0.6
Moderate	2.5	2.7
Major	75	42
Collapse	230	110

Figure 3.13 Normal distribution model for bridge restoration (FEMA HAZUS, 2003).

3.5 Monte Carlo Simulation

Monte Carlo technique is one of the computational simulation approaches that rely on random sampling to obtain numerical results. The main concept of Monte Carlo Simulation is to estimate the mean value of the response of a complex system by using a reasonable subset of solution space. The subspace is determined by sampling the original space which means that a sufficient number of simulation times to obtain a reliable result should be found before a real analysis. In this study, Monte Carlo technique is applied to simulate bridge restoration process based on stochastic models of bridge repair progress, and this simulation is eventually reflected in social loss relating to traffic impairment due to seismic damage of highway traffic network. Therefore, an exploratory convergence study on Monte Carlo Simulation for the final result (i.e., social loss) is performed for identifying the reasonable simulation time. The several results on different simulation times are presented in Figure 3.14. According to this graph, the result on 400 times is almost stable compared to 1,000, 2,000 and 5,000 times. The results of social loss are $5.58 \cdot 10^7$, $5.58 \cdot 10^7$, $5.59 \cdot 10^7$ and $5.57 \cdot 10^7$ (day·hour), respectively. With a small number of simulation times (i.e. 10 and 50), Monte Carlo technique cannot derive the stable solution or show the validity of final result. The solution is still streaky with 100 or 200 simulation times. From this result of convergence study, 400 times' simulation is reasonably stable as indicated in Figure 3.14 and is adopted for Monte Carlo Simulation of this research. As examples of Monte Carlo Simulation, the averaged restoration curve and all simulated restoration curves of social loss on several simulation times are illustrated in Figure 3.15.

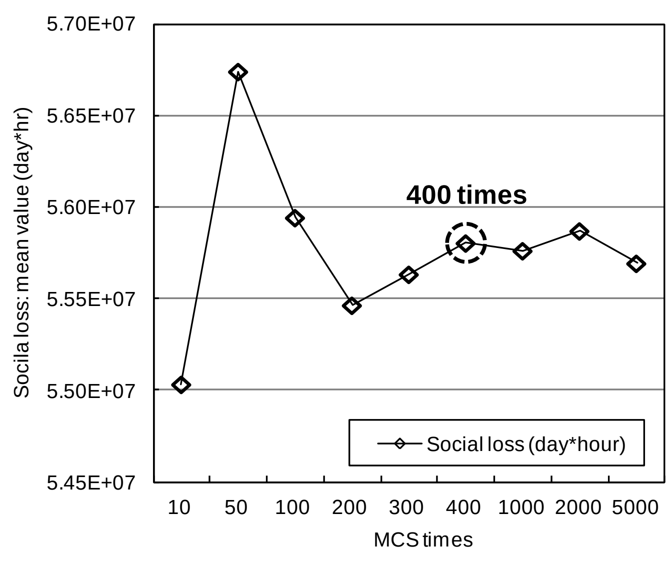


Figure 3.14 Reasonable times for Monte Carlo Simulation.

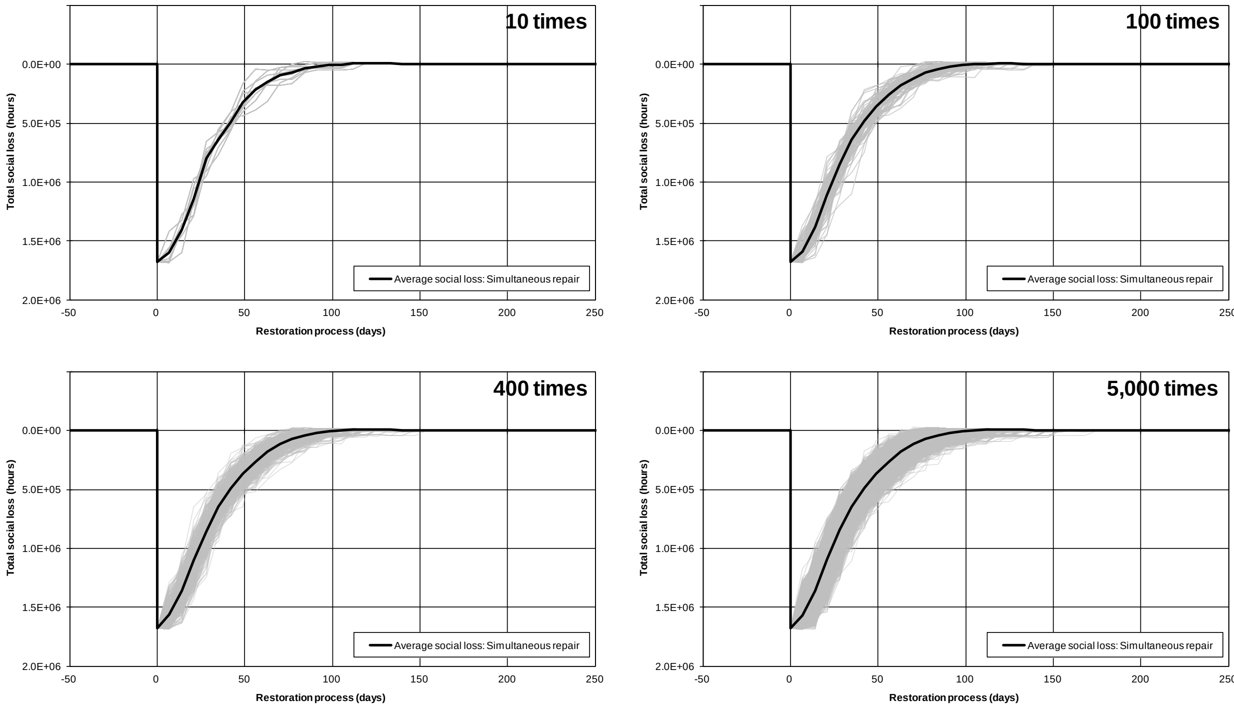


Figure 3.15 Examples of Monte Carlo Simulation for restoration process.

Chapter 4

Model verification

The original highway network model has been applied to several researches as mentioned in chapter 2 and has been improved at each time (Shiraki et al., 2000 & 2007, Shinozuka et al., 2003 & 2005, Zhou, 2006 and Zhou et al., 2010). On the other hand, the model has not been verified its validity by actual records of seismic damage. It is true that the verification task for the model of post-earthquake restoration process is very difficult for a lack of data about actual reconstruction process, but the developed model needs to be confirmed its applicability not only for making it more accurate but also for giving it more reliability from the standpoint of decision making. This study therefore compares an estimation of seismic loss caused by highway interruption at Northridge earthquake with results by the developed model for the purpose of model verification.

The Northridge earthquake is the most appropriate for this verification purpose because a large number of bridge damage data and seismic loss researches about this earthquake have been reported. Also, it induced severe damage of highway transportation network around Los Angeles area which is exact same as the area of this highway model. Therefore, the estimation of economic loss and drivers' delay relating to traffic interruption due to Northridge earthquake researched by Gordon et al. (1998) is adopted to compare with the simulation results estimated by the developed model. For this simulation, the actual bridge damage records and the earthquake intensity distribution documented at Northridge earthquake are utilized for reproducing the seismic damage status of the highway network. The importance criterion (i.e., based on intact traffic volume) is used for prioritizing repair order on the basis of the descriptions of actual orders in several documents. Then, the best suitable combination of the bridge restoration model and the level of residual traffic capacity are found, and its adequacy is confirmed by the comparison with the mentioned research estimations (Gordon et al., 1998). In addition, the comparing investigations between 3 bridge restoration models and 6 prioritized repair orders are conducted by the simulated results for grasping a changing trend of restoration processes and seismic losses which might have been possibly induced by Northridge earthquake. The verification study about post-earthquake restoration process of highway network is conducted by following the analysis flow as shown in Figure 4.1.

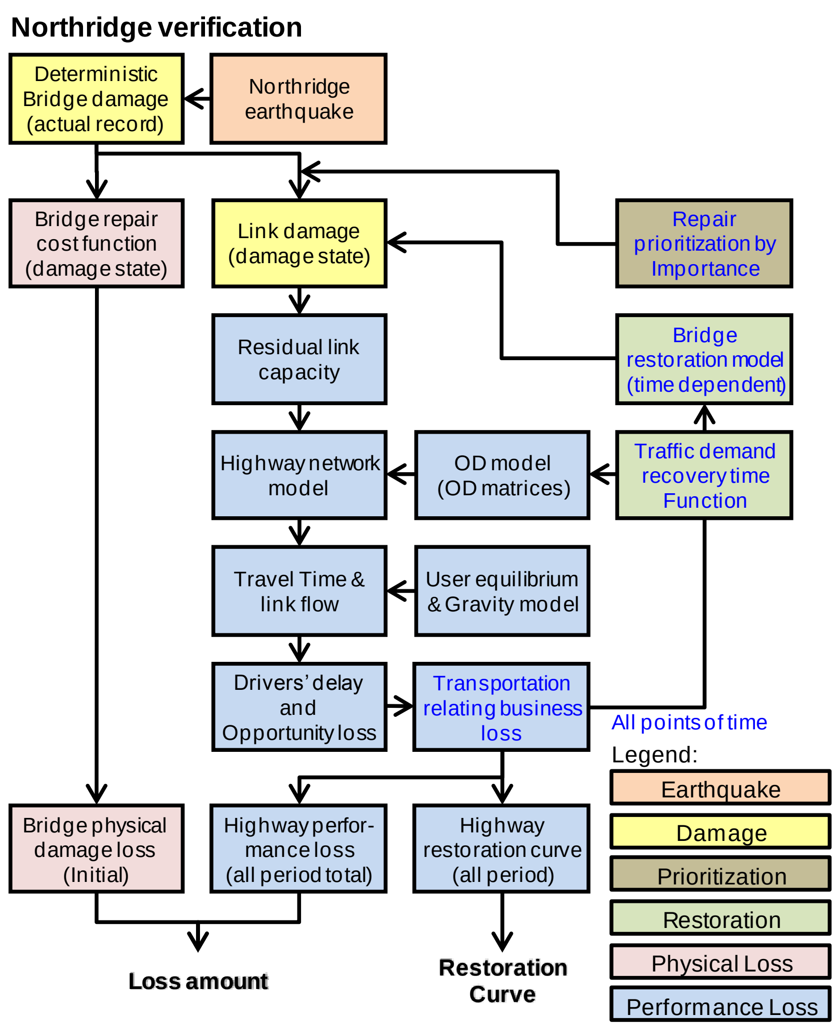


Figure 4.1 Analysis flow of model verification by Northridge earthquake.

4.1 Loss estimation at Northridge earthquake by Gordon et al., 1998

The total regional economic loss due to Northridge earthquake was estimated by many reports, but there are few researches which evaluated seismic loss only relating to highway transportation network disruption. The paper written by Gordon et al. in 1998 is the one which calculated the transport-related impacts due to Northridge earthquake. More specifically, this paper estimated business interruption impacts related to highway transportation at Northridge earthquake by using economic methodology, Input-Output analysis. These economic losses were analyzed corresponding to divided business areas and were categorized into four types of interruptions such as commuting, inhibited customer access, shipping disruption and supply disruption. Also, the additional travel time for commuting was estimated by using survey results of travel time losses. Thus, these highway-related seismic damages in terms of economy and time are usable for the verification study of the simulation model developed in this study.

From Gordon's paper, the summation of economic losses due to four types' transport-related interruptions is more than US$1.5 billion in 1994 U.S. dollars as shown in Table 4.1, and this total loss is about 27.3% of all local business impacts. The economic analysis of Gordon's paper aimed at the broader Los Angeles area such as Los Angeles, Orange, San Bernardino, Riverside and Ventura counties, so the loss occurred only in Los Angeles and Orange counties is believed to be less than the total, US$1.5 billion. However, this total amount of economic loss can be considered to apply to the verification study of this developed highway network model because the most of seismic damage happened in Los Angeles county. It is therefore presumed that there are not any difference between Gordon's total estimation and the evaluation by the developed model. In the paper, the additional travel time for commuter living in the impact zone (i.e., city of Los Angeles, Santa Monica, San Fernando and Glendale) is calculated by applying

Table 4.1 Loss estimation due to transportation interruption at Northridge earthquake (Gordon et al., 1998).

Zones	Economic loss due to transportation interruption (1994 US dollars [*1])				
	Commute	Customer access	Shipping	Supplies	Total
Impact zone [*2]	US$371,971,900	US$138,408,200	US$246,539,500	US$152,049,400	US$908,969,000
Rest of L.A. City	US$25,940,000	US$9,652,100	US$17,192,800	US$10,603,400	US$63,388,300
Rest of L.A. County	US$119,392,800	US$44,425,200	US$79,132,400	US$48,803,700	US$291,754,100
Rest of region	US$98,108,100	US$36,505,300	US$65,025,100	US$40,103,200	US$239,741,700
Region total	US$615,412,800	US$228,990,800	US$407,889,800	US$251,559,700	**US$1,503,853,100**

*1: Converter (deflator) from 1994 to 2012 = 1.42154.
*2: Cities of Los Angeles, Santa Monica, San Fernando, and Glendale.

Additional travel time for commuters living in Impact zone (from home in Impact zone to work place) =	**6,570,000 hours**

* Survey focused on four free way: I-5, SR-14, SR-118, and I-10 (severe damaged highways).
* "then travel time losses of workers living outside Impact zone" was not considered.
* "then travel time losses associated with nonwork travel" was not considered.

the averaged loss of travel time of commuting employees in the survey to total employment by residence in the impact zone. The calculation generates 6.57 million hours (one-way) in total as indicated in Table 4.1. In contrast to the economic losses in the paper, this additional time is estimated only in the impact zone, so the drivers' delay simulated by the model might be overestimated. However, little highway damage happened in Orange county and the impact zone encompasses most of the damaged road segments at Northridge earthquake, so the additional time in the paper is assumed to be appropriate for the verification study. Since this estimation is based on one-way commuting, the half of drivers' delay time of home-work trip type is compared with 6.57 million hours.

4.2 Verification analysis

The verification analysis is performed under specific analytical conditions by applying actual bridge damage data and earthquake intensity caused by Northridge earthquake. The verification analysis follows the same procedure of the established methodology, so the simulation results are derived through Monte Carlo Simulation. The importance criterion is primarily used for deciding repair order to recreate post-earthquake progress at Northridge earthquake, but other five criteria are also applied to prioritize bridge reconstruction orders for the purpose of comparison study about prioritization. The detailed analysis conditions, the initial damage states and the prioritized restoration orders are described in the following three sections.

4.2.1 Analysis conditions

The simulation for model verification is analyzed based on the actual extent of bridge damage and seismic intensity due to Northridge earthquake. Therefore, the initial damage status of highway network has to reproduce the actual damage situation at Northridge earthquake. The detailed conditions of analysis are indicated in Figure 4.2. The limited regional labor for constraining reconstruction progress is set 3,000 as daily maximum calibrated in section 3.3.3, and the importance criterion for prioritizing repair order is adopted for this verification study on

Initial damage state	: Actual bridge damage due to Northridge earthquake
Repair priority	: Importance (additionally, other five priorities)
Limited regional labor	: 3,000 (additionally, Unlimited)
Bridge restoration model	: Markov Chain Process, Uniform distribution, Normal distribution
Residual traffic capacity	: Moderate, High and Low

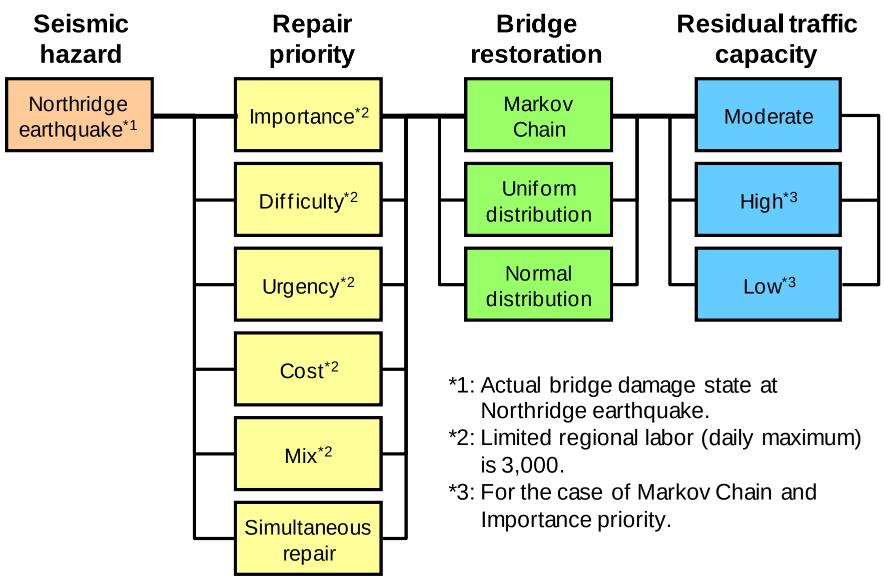


Figure 4.2 Analysis conditions for model verification by Northridge earthquake.

the basis of documented actual orders. Additional five prioritization criteria are employed for simulating other post-earthquake scenarios due to different repair orders for understanding the changing trend of restoration curves. Markov Chain process model, Uniform distribution model and Normal distribution model proposed in section 3.4 are considered for representing bridge restoration process which directly effects on the progress of traffic performance recovery, and the most suitable model is identified and verified by comparing with Gordon's estimation introduced in the previous section. For the verification of level of residual traffic capacity, three rates of residual capacity indicated in section 2.5 are applied to the most suited bridge restoration model. The capacity rate closest to Gordon's estimation is then found out from low, moderate and high capacities.

4.2.2 Bridge and link damage state

The bridge damage due to Northridge earthquake applied to the simulation model is based on the actual damage data investigated by Caltrans, and the distribution of the damage status is illustrated in Figure 4.3. In this figure, the epicenter of Northridge earthquake is plotted by a star mark, and larger circle indicates severer damage status. The damage situation is that collapsed bridges are 9, major damaged bridges are 44, moderate damaged bridges are 89 and minor damaged bridges are 80. The total number of damaged bridges is therefore 222. Severer damaged bridges are basically distributed around the epicenter, and there are not any damaged bridges in Orange county. Based on this bridge damage status, the link damages due to Northridge earthquake are identified and shown in Figure 4.4. In this figure, the epicenter of Northridge earthquake is also plotted by a star mark, and different colors are used for representing link damage states as defined in the map legend. The link damage situation is that collapsed links are 10, major damaged links are 34, moderate damaged links are 40 and minor

Figure 4.3 Bridge initial damages at Northridge earthquake based on the records.

Figure 4.4 Link initial damages at Northridge earthquake based on bridge damages.

damaged links are 32. The total number of damaged links is then 116 (considering round trip). However, the total number of links which are disrupted traffic capacity is 84 because the minor damaged link is assumed to be able to keep 100% capacity in this study. Impaired links (i.e., pink, orange and green colored routes) are spread around the epicenter corresponding to the bridge damage distribution.

4.2.3 Prioritized repair order

The information of exact bridge reconstruction order at Northridge earthquake is not remained publicly. Therefore, the repair order of damaged bridges in this verification study is determined based on the importance criterion because this criterion is considered the most appropriate for prioritizing repair order from the partial records about reconstruction start and completion date of some bridges at Northridge earthquake. The repair order prioritized by importance factor through Analytic Hierarchy Process algorithm established in section 3.2 is depicted in Figure 4.5. In this figure, larger circle denotes earlier repair order in the figure and the bridges repaired within the first quartile order of all are displayed by red and pink color. The bridges in earlier orders are concentrated in the routes of I-10, I-5, SR-118 and I-405 in western and northwestern parts of Los Angeles metropolitan area because of heavier traffic volume at ordinary time. Some records are in consistency with this estimated repair orders. For instance, the reconstruction work of collapsed bridges on route I-10 indicated in Table 3.2 were started from February 5 (about 2 weeks after the earthquake occurred), and the operations of demolition and shoring are therefore supposed to be begun right after the earthquake. Also, one of the bridges on route SR-118 shown in Table 3.2 was repaired from February 10, and the preparatory reconstruction works can be assumed to be started immediately following the earthquake. Thus, some actual records of bridge repair works are accorded with this estimated repair order.

Figure 4.5 Prioritized repair order for Northridge earthquake on Importance.

Therefore, the evaluated order prioritized by importance criterion here is ascribed to reproduce the actual bridge repair order at Northridge earthquake.

The analyzed repair orders based on other criterion are shown in Figure 4.6 to Figure 4.9, and they are prioritized by difficulty, urgency, cost and mix criterion, respectively. These repair orders are used for comparison study about repair prioritization. Since three criteria shown here, difficulty, urgency and cost, are somehow related to the bridge damage state (i.e., slighter damage is earlier repair order in a simple term), there can be recognized similar tendencies between their repair orders. For example, in the case of these three orders, the bridges suffered minor or moderate damage in Los Angeles downtown area are restored much earlier compared to their orders prioritized by importance criterion, and the reconstruction for damaged bridges in Long Beach area and Santa Clarita area are also started in earlier order. The order presented at the end is based on mix criterion, and it is derived from equal weighting of four criteria.

Figure 4.6 Prioritized repair order for Northridge earthquake on Difficulty.

Figure 4.7 Prioritized repair order for Northridge earthquake on Urgency.

Figure 4.8 Prioritized repair order for Northridge earthquake on Cost.

Figure 4.9 Prioritized repair order for Northridge earthquake on Mix priority.

4.3 Time and economic loss verification

A sequence of analyses of the developed methodology are implemented based on the conditions set in the previous section, and social loss (i.e., sum of drivers' delay and opportunity loss) restoration curve and economic loss are finally estimated for all cases through traffic network analysis. The reasonability of developed model and simulation results are then confirmed in terms of both economic loss and additional driving time by comparative verification with Gordon's estimation (1998). The applicability of bridge restoration model and the properness of level of residual traffic capacity are examined through these time and economic loss verifications, and the most adequate bridge model and capacity level are then identified and applied to an application example in the next chapter.

4.3.1 Bridge restoration model verification

The restoration curves of social loss, drivers' delay and opportunity loss simulated by Markov Chain process model, Uniform distribution model and Normal distribution model are shown in Figure 4.10 to Figure 4.12, respectively. In addition, the restoration curves of same kind of loss by three restoration models are put in a same graph for model comparison, and they are presented in Figure 4.13 to Figure 4.15. Here, the moderate rate of residual traffic capacity is applied to traffic network analyses of all cases, and the specific studies about residual capacity vilification are conducted in the next section. In the figures, the total loss during entire restoration period which is integrated from Day 0 to completion day is also calculated and indicated. The total social losses of Markov Chain process model and Normal distribution model are almost same, 92,290,980 hours and 97,791,130 hours. The same is true of the total drivers' delay and the total opportunity loss. Also, the restoration processes about these three losses of this two models are nearly identical from the comparison of these restoration curves although the

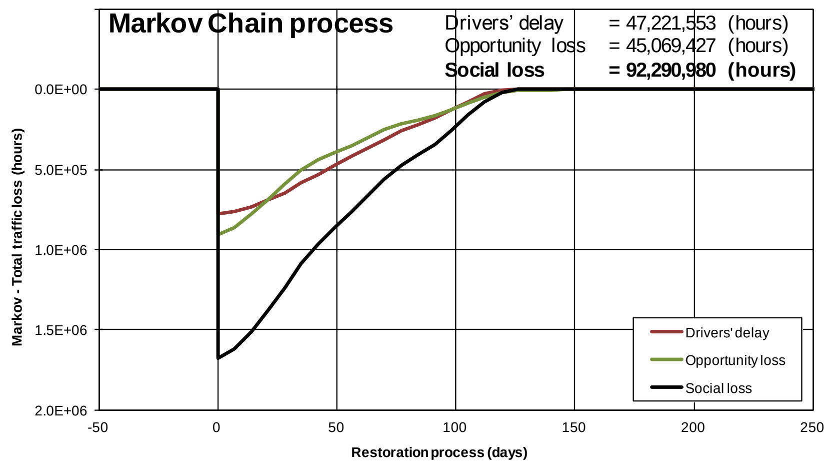


Figure 4.10 Social loss restoration curve: Markov Chain process model.

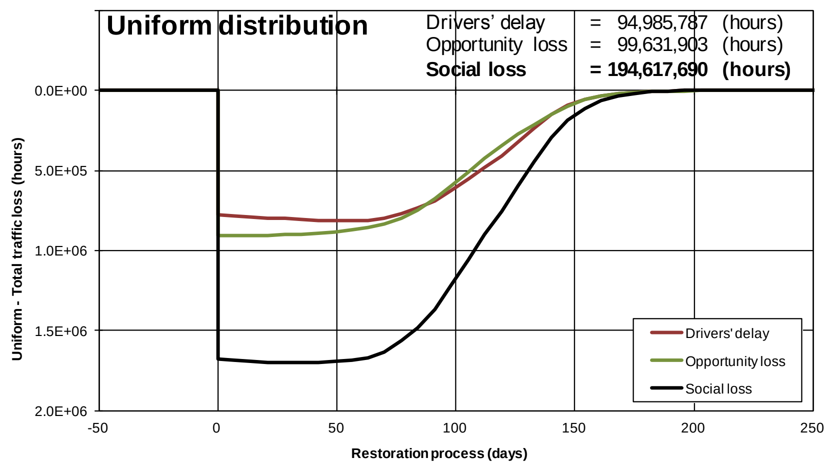


Figure 4.11 Social loss restoration curve: Uniform distribution model.

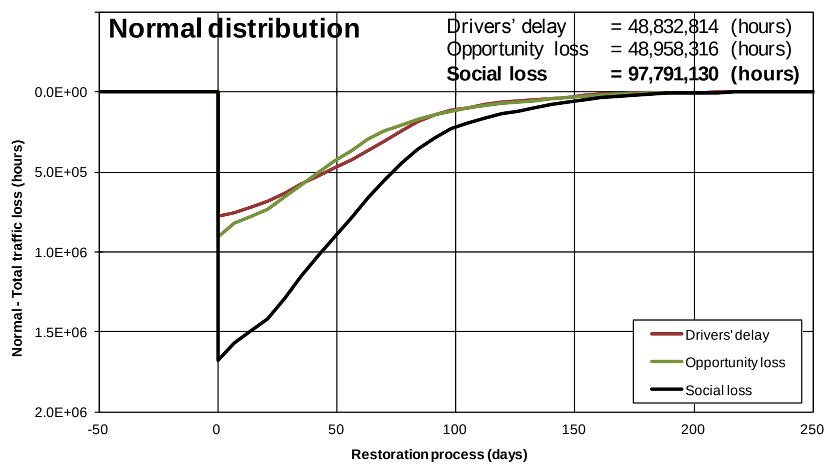


Figure 4.12 Social loss restoration curve: Normal distribution model.

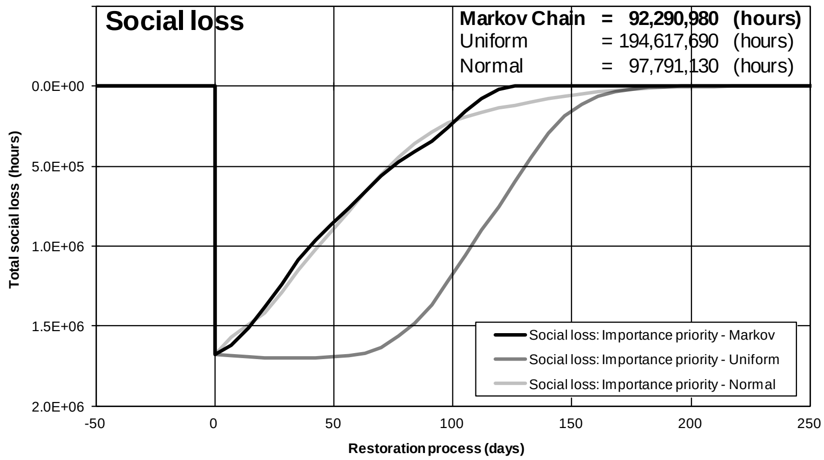


Figure 4.13 Social loss restoration curve: comparison of 3 models.

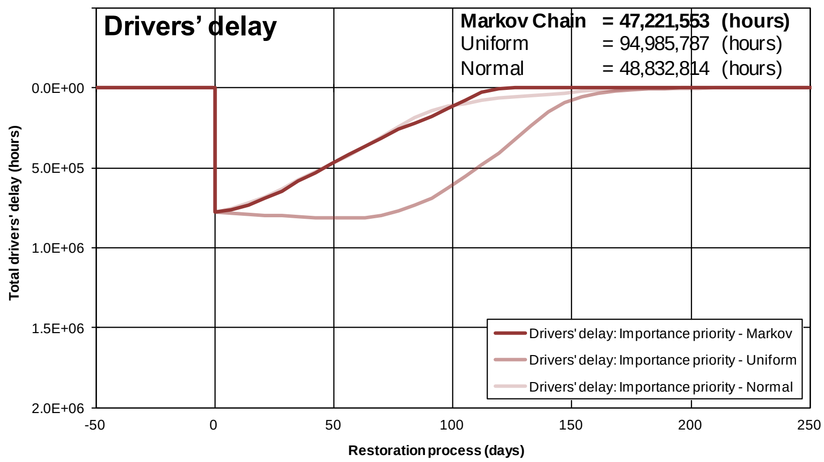


Figure 4.14 Drivers' delay restoration curve: comparison of 3 models.

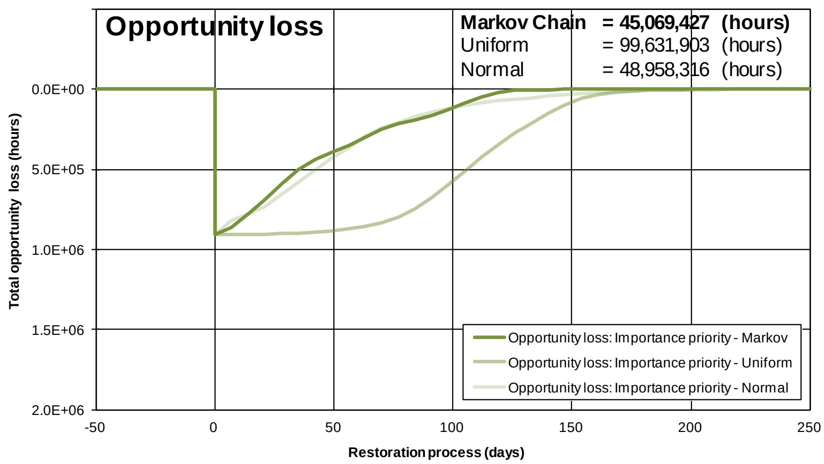


Figure 4.15 Opportunity loss restoration curve: comparison of 3 models.

closing stage of restoration of Normal distribution model is a little slower than that of Markov Chain process model. On the other hand, the total social loss of Uniform distribution model is almost double of the others, 194,617,690 hours, and the same tendency can be seen in the cases of drivers' delay and opportunity loss. The most possible cause is the difference of restoration progress at the beginning. The recovery work in the first 70 days is simulated less-advanced by Uniform distribution model compared to other two models, though the recovery speed (i.e., gradient of curve) during the mid-period of all restoration models can be considered to be at almost the same pace. The bar-charts shown in Figure 4.16 represent the monetary value of social losses of three models (i.e., economic loss). The economic social loss put in the upper chart is converted from time unit of total social loss by applying the averaged unit cost of drivers' time described in section 2.8, and it is represented in 2012 U.S. dollars. The lower chart is then

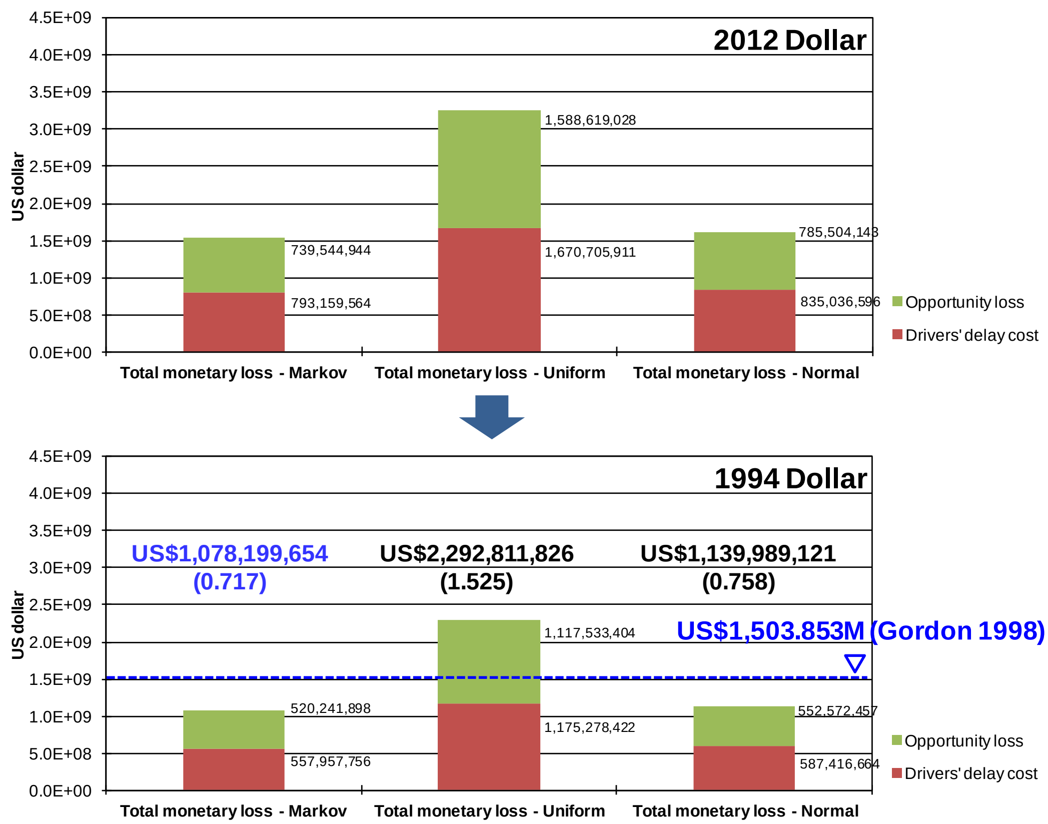


Figure 4.16 Monetary value of social loss of 3 models.

obtained by transforming their monetary values from 2012 U.S. dollars to 1994 U.S. dollars through the deflator, 1.42154. Compared to the economic loss of Gordon's estimation (1998), US$ 1,503,853,100, added in the lower graph by a blue dot-line, the total economic losses of Markov Chain process model and Normal distribution model, US$ 1,078,199,654 and US$ 1,139,989,121, are not away from Gordon's estimation, and they are about 70% or 80% of Gordon's. These two simulated losses are therefore deemed to be at the same level as Gordon's evaluation. However, the loss of Uniform distribution model, US$ 2,292,811,826, is well over Gordon's and is more than one and half times of that.

The restoration curves of drivers' delay regarding home-work trip (i.e., commuting trip) type simulated by Markov Chain process model, Uniform distribution model and Normal distribution model are shown in Figure 4.17 to Figure 4.19, respectively. A comparison figure of restoration curves by these three restoration models is presented in Figure 4.20. A half of the total drivers' delay (i.e., delay time for one-way trip) of Markov Chain process model and Normal distribution model are almost same, 11,576,178 hours and 11,545,626 hours. And, the restoration processes of this two models follow almost the same passage as shown in Figure 4.20 although the last period of restoration of Normal distribution model is a little longer than that of Markov Chain process model. In the meantime, a half of the total drivers' delay of Uniform distribution model is almost double of the others, 20,075,133 hours. This tendency is same as that of total social loss, and the difference of early restoration process between three models is also thought to cause this disagreement. The additional travel time for commuter (one-way commuting) in Gordon's estimation (1998) is 6,570,000 hours. As compared to this Gordon's estimation, the delay time of Markov Chain process model and Normal distribution model are not apart from it. However, the result of Uniform distribution model is far beyond Gordon's

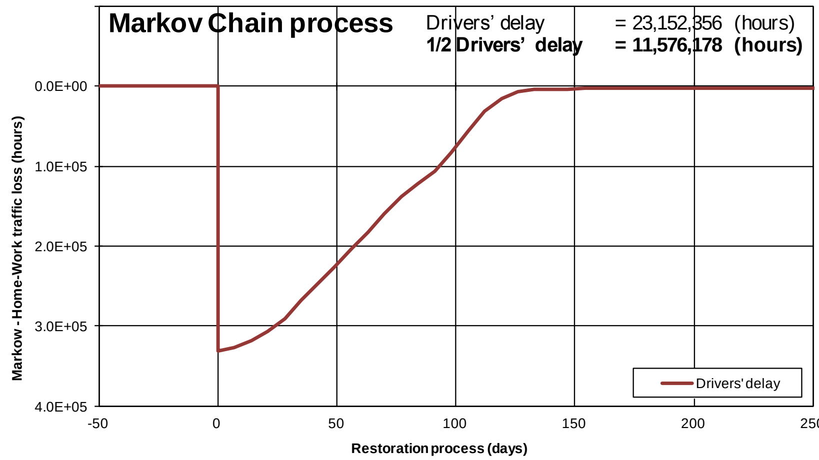


Figure 4.17 Home-Work drivers' delay restoration curve: Markov Chain process model.

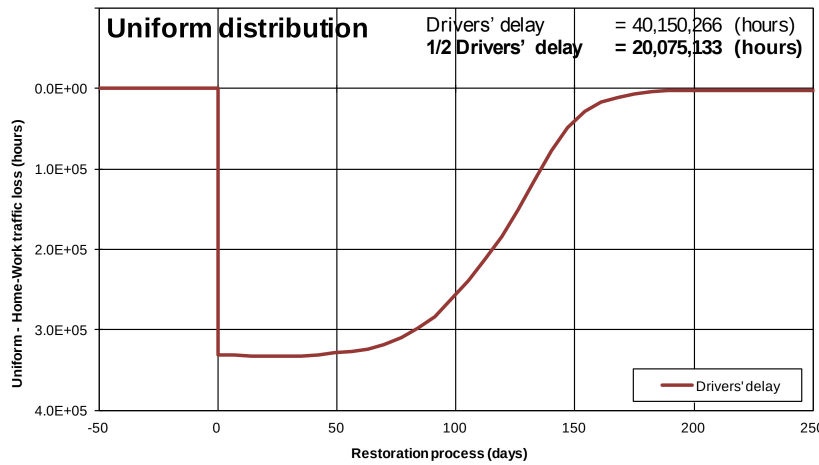


Figure 4.18 Home-Work drivers' delay restoration curve: Uniform distribution model.

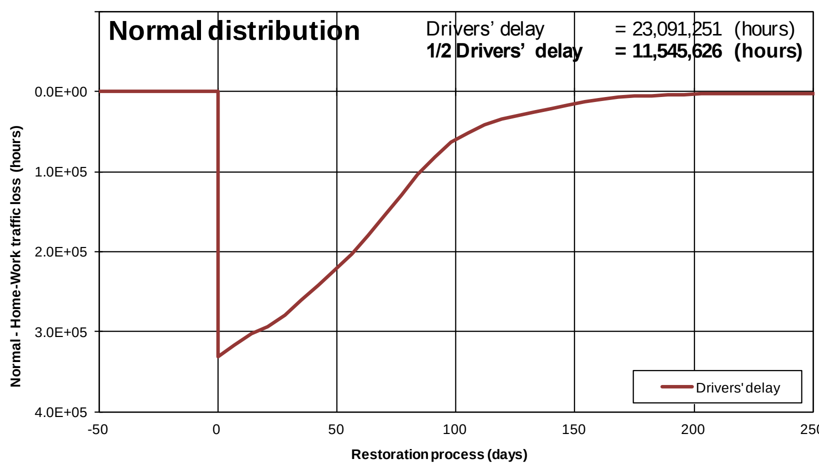


Figure 4.19 Home-Work drivers' delay restoration curve: Normal distribution model.

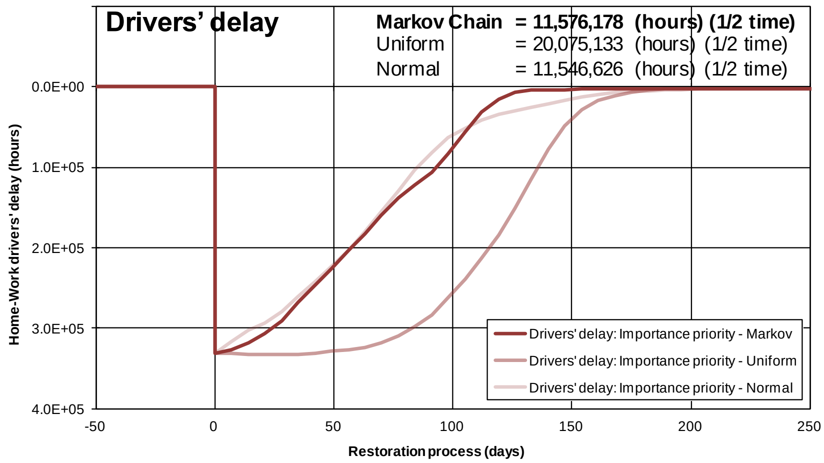


Figure 4.20 Home-Work drivers' delay restoration curve: comparison of 3 models.

estimation, about three times. Therefore, the drivers' delay results by the two restoration models except for Uniform distribution model are considered to be at the same level as Gordon's evaluation.

The comparison results suggest that the total social loss and drivers' delay of home-work & one-way trip of Markov Chain process model and Normal distribution model are almost same and are similar to Gordon's estimation (1998). Therefore, these two models would be able to simulate the restoration process accurately. On the other hand, the simulation results of Uniform distribution model is conservative (i.e., safety) compared with Gordon's estimation. In the case of comparing Markov Chain process model with Normal distribution model, the bridge restoration process at the initial period simulated by Normal distribution model (enclosed area by black dot-line) is assumed to be unable to consider any uncertainties (i.e., almost deterministic simulation) as shown in the right graph of Figure 4.21. This is because the smallness of mean values and standard deviations for minor and moderate damage of this model strongly effects on this phenomenon as described in section 3.4.3. On the contrary, there can be seen some effects of uncertainties during the whole recovery process simulated by Markov Chain process model as shown in the left graph of Figure 4.21. As a result, Markov Chain process model is believed to be more appropriate for reproducing bridge restoration progress than Normal distribution model, and Markov Chain process model is therefore verified its applicability by the seismic loss estimation of Northridge earthquake.

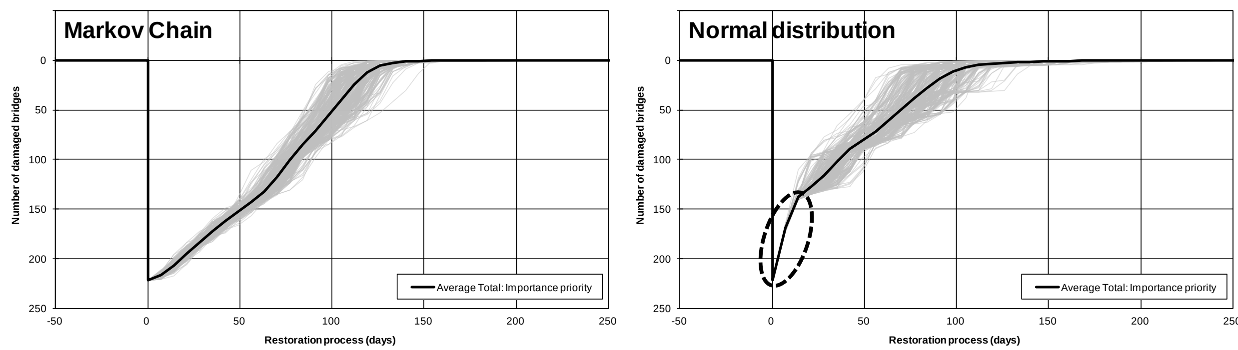


Figure 4.21 Comparison of simulations on Markov Chain process and Normal distribution.

4.3.2 Residual traffic capacity verification

Based on the result of the previous section, the restoration curves of social loss, drivers' delay and opportunity loss simulated only by Markov Chain process model with three levels of residual traffic capacity are shown in Figure 4.22 to Figure 4.24, respectively. In addition, the restoration curves of same kind of loss by three traffic capacity levels are put in a same graph for model comparison, and they are presented in Figure 4.25 to Figure 4.27. In the figures, the total losses during entire restoration period are noted. The total social loss of moderate traffic capacity is 92,290,980 hours, that of low traffic capacity is 271,736,624 hours (about 3 times of moderate's case), and that of high traffic capacity is 27,889,929 hours (about 30% of moderate's case). Thus, the total losses differ greatly between 3 capacity levels as expected by their rates shown in Table 2.2, and the same is true of the total drivers' delay and the total opportunity loss. Also, the restoration processes about these three losses of three capacity levels are profoundly different depending strongly on the initial amount of performance loss. Since the initial damage

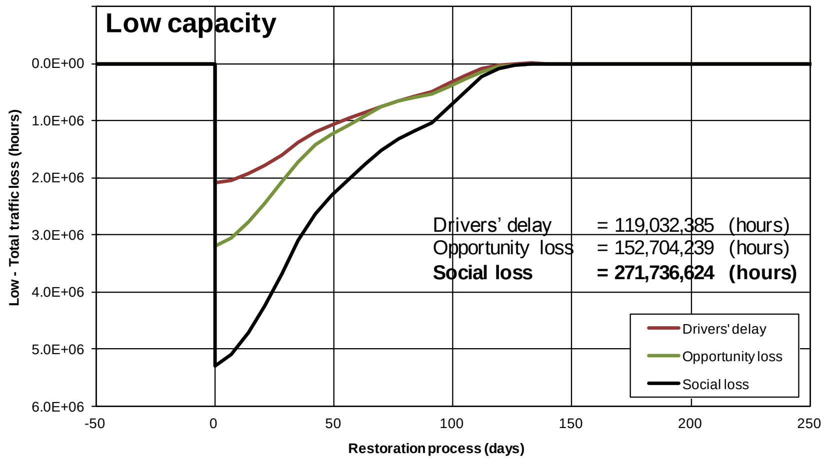


Figure 4.22 Social loss restoration curve: Low residual capacity.

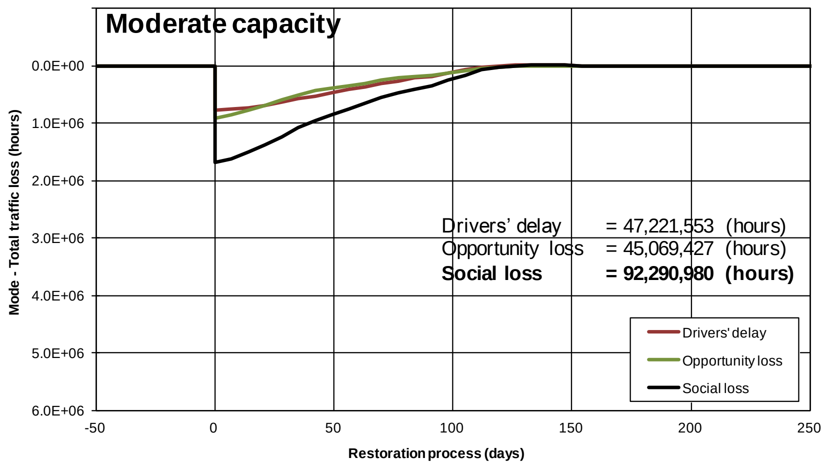


Figure 4.23 Social loss restoration curve: Moderate residual capacity.

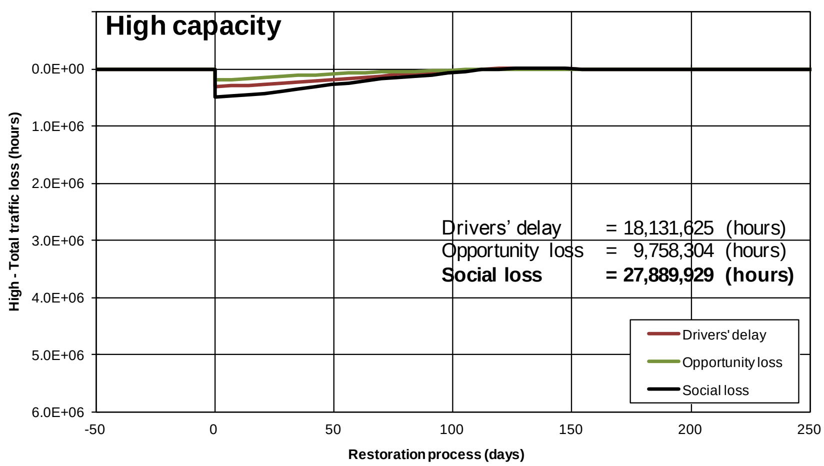


Figure 4.24 Social loss restoration curve: High residual capacity.

Figure 4.25 Social loss restoration curve: comparison of 3 residual capacities.

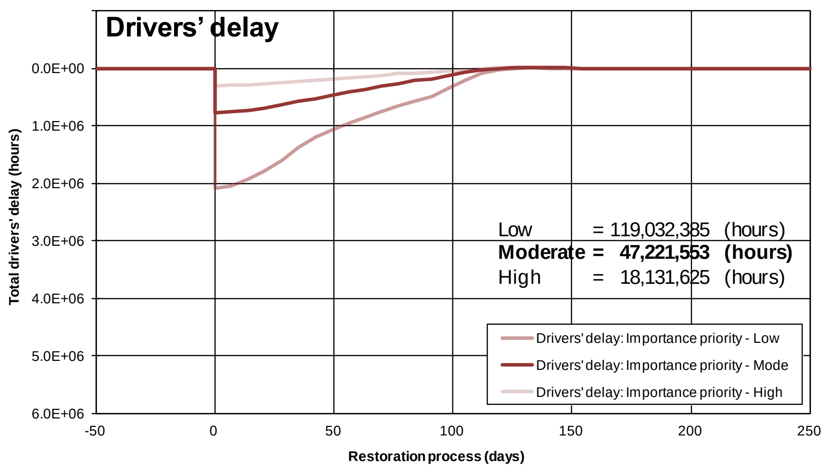


Figure 4.26 Drivers' delay restoration curve: comparison of 3 residual capacities.

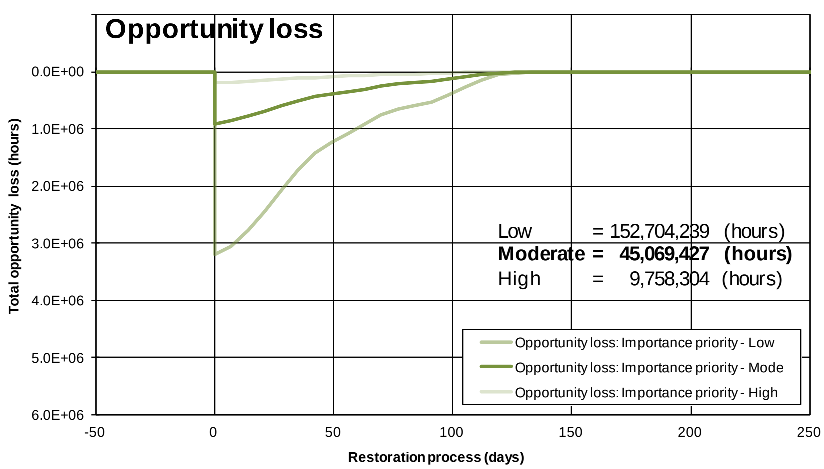


Figure 4.27 Opportunity loss restoration curve: comparison of 3 residual capacities.

status of bridges and links and the bridge restoration model are identical between three cases, those differences only come from the setting of decreasing rate of traffic capacity. Therefore, the specification and verification of proper residual traffic capacity due to earthquake is important for traffic network simulation. The bar-charts shown in Figure 4.28 express the monetary value of social losses of three cases. The economic social loss put in the upper chart represented in 2012 U.S. dollars is converted from time unit of total social loss by applying the averaged unit cost of drivers' time as well as the previous section. The lower chart is then obtained by transforming their monetary values from 2012 U.S. dollars to 1994 U.S. dollars. Compared to the economic loss of Gordon's estimation (1998), US$ 1,503,853,100, the total economic losses of moderate traffic capacity, US$ 1,078,199,654 is not away from Gordon's estimation, and it is about 70% of Gordon's. This simulated loss based on moderate capacity is therefore considered

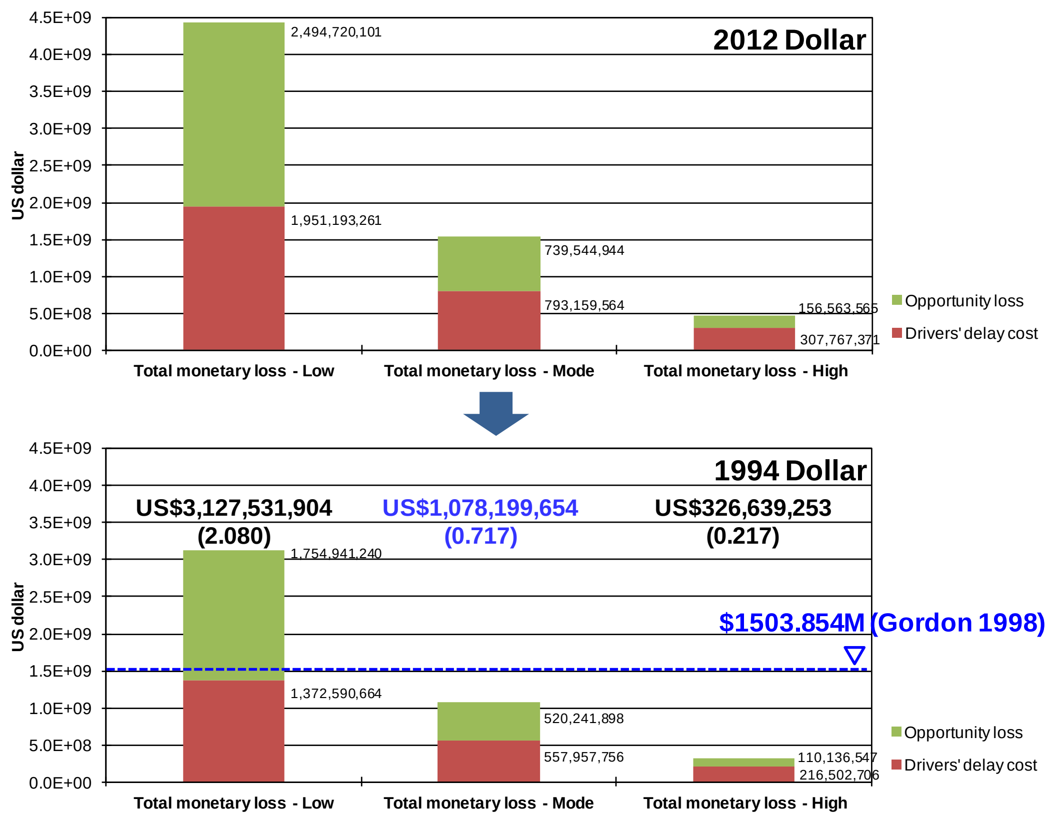


Figure 4.28 Monetary value of social loss of 3 residual capacities.

to be at the same level as Gordon's evaluation. However, the losses based on low traffic capacity and high traffic capacity, US$ 3,127,531,907 and US$ 326,639,253, are considerably over and below Gordon's, and they are about double and one-fifth of that.

The restoration curves of drivers' delay regarding home-work trip type simulated by Markov Chain process model with three levels of residual traffic capacity are shown in Figure 4.29 to Figure 4.31, respectively. A comparison figure of restoration curves based on these three traffic capacity levels is presented in Figure 4.32. A half of the total drivers' delay of moderate traffic capacity is 11,576,178 hours. In the meantime, a half of the total drivers' delay of low traffic capacity and high traffic capacity are 20,301,061 hours and 5,692,424 hours, respectively. The trend of effect of initial performance loss difference is same as that of total social loss. The additional travel time for commuter in Gordon's estimation (1998) is 6,570,000 hours. As compared to this Gordon's estimation, the delay time of moderate traffic capacity and high traffic capacity are not far from it. However, the result of low traffic capacity is far beyond Gordon's estimation, about three times. Therefore, the drivers' delay results by the two levels of traffic capacity except for low traffic capacity are considered to be at the same level as Gordon's evaluation.

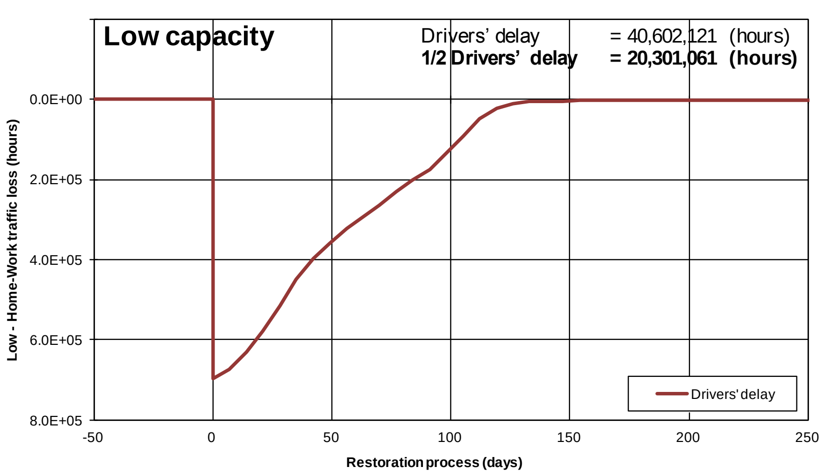


Figure 4.29 Home-Work drivers' delay restoration curve: Low residual capacity.

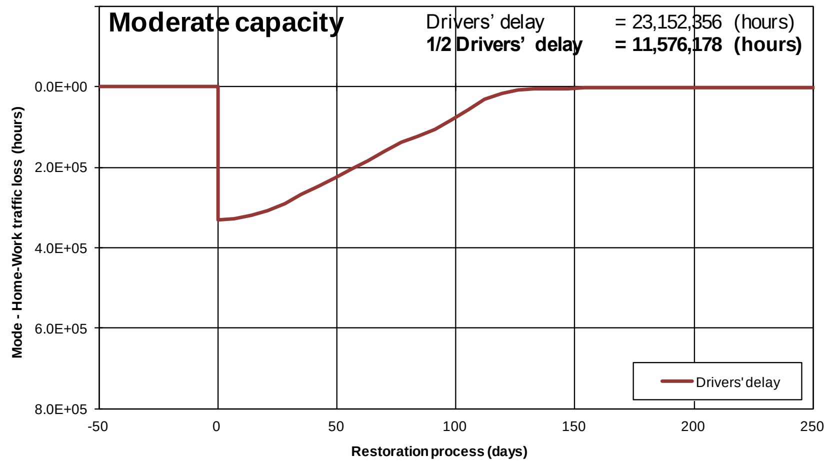


Figure 4.30 Home-Work drivers' delay restoration curve: Moderate residual capacity.

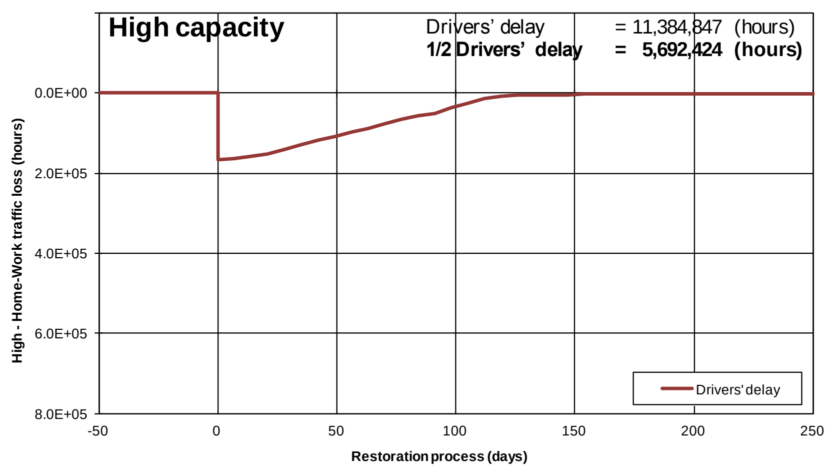


Figure 4.31 Home-Work drivers' delay restoration curve: High residual capacity.

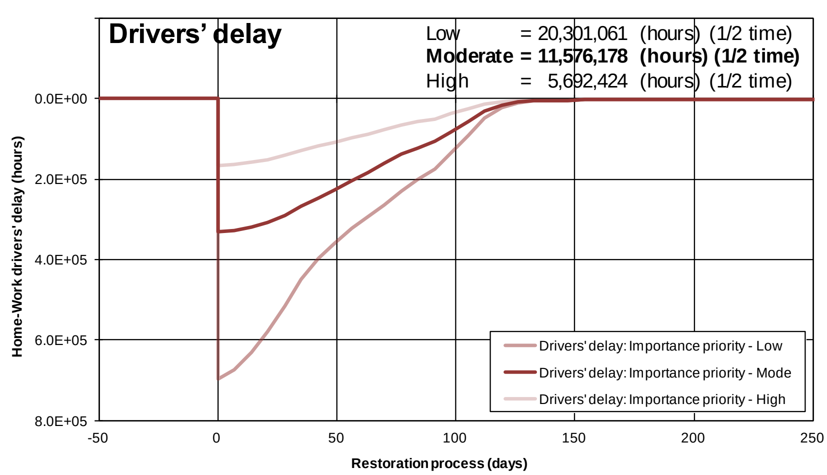


Figure 4.32 Home-Work drivers' delay restoration curve: comparison of 3 capacities.

The result of comparison studies show that the simulation based on low residual traffic capacity is thought to overestimate the total social loss compared with the loss estimation of Northridge earthquake by Gordon et al. (1998). From the comparison of drivers' delay of home-work trip between moderate capacity and high capacity, it is true that the error from Gordon's estimation of high capacity is smaller than that of moderate capacity. However, the total social loss of high capacity is too far from Gordon's estimation to consider both results as same level, and it is underestimated very much compared to Gordon's. Therefore, moderate residual traffic capacity can be considered to be appropriate for reflecting post-earthquake traffic degradation, and the rate of moderate capacity is therefore verified its adequacy by the seismic loss estimation of Northridge earthquake.

4.4 Results

The applicability of bridge restoration model and residual traffic capacity for this post-earthquake simulation model are verified in this section. This verification study is done based on both the actual loss estimation of Northridge earthquake (Gordon et al., 1998) and the simulation results by the established model. Total social loss and drivers' delay of home-work trip during entire restoration period are used for comparative verification. The most adequate analysis set shown below is then identified from combinations of three restoration models and three levels of

Bridge restoration model : Markov Chain process model

Residual traffic capacity : Moderate residual traffic capacity

traffic capacity at this point. The simulated social loss and drivers' delay by Markov Chain process model and moderate traffic capacity are not exact same amount as Gordon's estimation, but it can be ascribed to stay at the same level of Gordon's evaluation because the difference between both loss amounts is not so large as pointed in the previous section. If more actual data would be collected and recorded, this verification study can be made more accurately and chronologically and contribute an exhaustive simulation of restoration process in the future. On the other hand, Uniform distribution model and/or low residual traffic capacity can be used in the case of conservative (i.e., safety) estimation, and Normal distribution model could be applied if the restoration progress during the beginning of recovery period is not focused.

4.5 Model comparison

The comparing studies between 3 bridge restoration models and 6 prioritized repair orders are performed based on Northridge earthquake simulations in this section. The post-earthquake restoration process for highway network system is simulated with moderate residual traffic capacity, actual bridge damage status due to Northridge earthquake and seismic intensity distribution of Northridge earthquake for all cases. 3,000 workforces are applied as the number of maximum regional labor to constraint the progress of reconstruction work. Here, the repair order corresponding to each prioritization criterion is same for three simulations based on three different bridge restoration models because the repair order is decided numerically and systematically from the same states of initial bridge damage through Analytical Hierarchy Process. Therefore, the distinctions of recovery processes arose from different models can be observed apparently and be compared each other. In addition, different passages of reconstruction work depending on repair orders by the same bridge restoration model can be scrutinized individually and be compared mutually.

The bridge repair orders for Northridge earthquake damage status are evaluated according to each prioritization criteria such as difficulty, importance, urgency, cost and mix. Those prioritized orders with priority values for all 222 damaged bridges are shown in Table 4.2.

Table 4.2 Prioritized repair order at Northridge earthquake corresponding to criteria.

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
1	293	1	1.471E-02	1233	2	1.141E-02	1113	1	5.838E-03	1113	1	1.390E-01	1113	1	3.904E-02
2	2185	1	1.471E-02	1229	2	1.141E-02	1188	1	5.838E-03	1188	1	9.333E-02	1188	1	2.848E-02
3	1504	1	1.471E-02	1255	2	1.129E-02	1890	1	5.838E-03	1890	1	5.955E-02	1890	1	2.042E-02
4	1113	1	9.806E-03	1256	2	1.129E-02	1856	1	5.838E-03	1856	1	3.436E-02	1856	1	1.439E-02
5	1188	1	9.806E-03	1268	1	9.953E-03	1854	1	5.838E-03	1854	1	3.398E-02	1854	1	1.430E-02
6	1890	1	9.806E-03	1296	1	9.340E-03	1460	1	5.838E-03	1460	1	3.006E-02	1460	1	1.059E-02
7	1856	1	9.806E-03	1284	2	9.340E-03	293	1	5.838E-03	1426	2	2.021E-02	293	1	9.566E-03
8	1854	1	9.806E-03	1289	3	9.340E-03	2185	1	5.838E-03	1577	2	1.832E-02	1577	2	9.222E-03
9	1184	1	9.806E-03	716	1	9.036E-03	1184	1	5.838E-03	455	1	1.718E-02	2185	1	9.074E-03
10	455	1	9.806E-03	738	2	9.036E-03	455	1	5.838E-03	1449	2	1.675E-02	1184	1	8.633E-03
11	1537	1	9.806E-03	730	1	9.036E-03	533	1	5.838E-03	293	1	1.458E-02	455	1	8.426E-03
12	99	1	9.806E-03	735	1	9.036E-03	1537	1	5.838E-03	1184	1	1.396E-02	533	1	7.914E-03
13	1721	1	9.806E-03	733	1	9.036E-03	1562	1	5.838E-03	2185	1	1.303E-02	1537	1	7.651E-03
14	1919	1	9.806E-03	743	1	9.036E-03	716	1	5.838E-03	1998	2	1.254E-02	1449	2	7.474E-03
15	1709	1	9.806E-03	724	1	9.036E-03	537	1	5.838E-03	533	1	1.236E-02	1426	2	7.362E-03
16	857	1	9.806E-03	723	1	9.036E-03	99	1	5.838E-03	1532	3	1.120E-02	1562	1	7.310E-03
17	1913	1	9.806E-03	725	1	9.036E-03	1721	1	5.838E-03	1562	1	1.115E-02	716	1	6.918E-03
18	963	1	9.806E-03	732	1	9.036E-03	1830	1	5.838E-03	1537	1	1.022E-02	1998	2	6.857E-03
19	825	1	9.806E-03	742	1	9.036E-03	1504	1	5.838E-03	1830	1	1.015E-02	537	1	6.829E-03
20	95	1	9.806E-03	739	2	9.036E-03	1919	1	5.838E-03	1919	1	9.532E-03	99	1	6.740E-03
21	2035	1	9.806E-03	727	2	9.036E-03	1709	1	5.838E-03	1501	2	8.684E-03	1721	1	6.710E-03
22	78	1	9.806E-03	715	2	9.036E-03	857	1	5.838E-03	1913	1	8.315E-03	1830	1	6.709E-03
23	1577	2	7.354E-03	741	4	9.036E-03	1913	1	5.838E-03	99	1	8.271E-03	1255	2	6.557E-03
24	533	1	7.354E-03	699	1	8.560E-03	963	1	5.838E-03	537	1	8.016E-03	738	2	6.520E-03
25	1449	2	7.354E-03	700	1	8.560E-03	1296	1	5.838E-03	716	1	7.895E-03	1504	1	6.404E-03
26	1998	2	7.354E-03	696	2	8.560E-03	730	1	5.838E-03	738	2	7.895E-03	1919	1	6.404E-03
27	537	1	7.354E-03	709	2	8.560E-03	825	1	5.838E-03	152	1	7.570E-03	1709	1	6.367E-03
28	1501	2	7.354E-03	706	2	8.560E-03	735	1	5.838E-03	75	1	7.444E-03	857	1	6.297E-03
29	1227	1	7.354E-03	710	2	8.560E-03	733	1	5.838E-03	1800	2	6.460E-03	1913	1	6.100E-03
30	75	1	7.354E-03	711	3	8.560E-03	743	1	5.838E-03	1809	2	6.460E-03	963	1	5.952E-03
31	555	1	7.354E-03	708	3	8.560E-03	724	1	5.838E-03	1457	1	6.380E-03	1296	1	5.898E-03
32	536	1	7.354E-03	705	3	8.560E-03	723	1	5.838E-03	1255	2	5.790E-03	730	1	5.858E-03
33	103	1	7.354E-03	714	4	8.560E-03	725	1	5.838E-03	1747	1	5.747E-03	825	1	5.833E-03
34	1496	1	7.354E-03	713	4	8.560E-03	732	1	5.838E-03	1204	3	5.437E-03	735	1	5.821E-03
35	454	1	7.354E-03	1721	1	8.237E-03	1268	1	5.838E-03	150	2	5.234E-03	733	1	5.810E-03
36	122	1	7.354E-03	1227	1	7.567E-03	1227	1	5.838E-03	1916	1	5.142E-03	743	1	5.773E-03
37	294	2	7.354E-03	1215	1	7.567E-03	699	1	5.838E-03	1205	3	5.104E-03	1233	2	5.748E-03
38	295	2	7.354E-03	1214	2	7.567E-03	1852	1	5.838E-03	1463	2	4.926E-03	724	1	5.726E-03
39	72	1	7.354E-03	1856	1	7.562E-03	1853	1	5.838E-03	825	1	4.916E-03	1501	2	5.722E-03
40	2460	1	7.354E-03	1854	1	7.562E-03	1884	1	5.838E-03	454	1	4.751E-03	723	1	5.669E-03
41	822	2	7.354E-03	1852	1	7.562E-03	75	1	5.838E-03	1884	1	4.571E-03	725	1	5.652E-03
42	1478	1	7.354E-03	1853	1	7.562E-03	742	1	5.838E-03	1709	1	4.521E-03	732	1	5.628E-03
43	1508	1	7.354E-03	1857	1	7.562E-03	555	1	5.838E-03	1256	2	4.424E-03	1268	1	5.623E-03
44	93	2	7.354E-03	1867	2	7.562E-03	536	1	5.838E-03	2170	1	4.225E-03	1227	1	5.611E-03
45	286	2	7.354E-03	1562	1	7.352E-03	1215	1	5.838E-03	1852	1	4.060E-03	1256	2	5.603E-03
46	296	2	7.354E-03	1574	3	7.352E-03	95	1	5.838E-03	136	2	4.057E-03	699	1	5.601E-03
47	70	2	7.354E-03	1522	1	6.997E-03	1857	1	5.838E-03	751	1	3.860E-03	1852	1	5.591E-03
48	1460	1	4.903E-03	1512	2	6.997E-03	1747	1	5.838E-03	106	1	3.722E-03	1532	3	5.556E-03
49	1426	2	4.903E-03	1515	2	6.997E-03	152	1	5.838E-03	730	1	3.657E-03	1229	2	5.533E-03
50	1562	1	4.903E-03	1520	3	6.997E-03	700	1	5.838E-03	72	1	3.652E-03	1853	1	5.475E-03
51	716	1	4.903E-03	1521	3	6.997E-03	1522	1	5.838E-03	1853	1	3.596E-03	1884	1	5.445E-03
52	1830	1	4.903E-03	1577	2	6.970E-03	1839	1	5.838E-03	1918	2	3.574E-03	75	1	5.387E-03
53	1255	2	4.903E-03	1586	2	6.970E-03	103	1	5.838E-03	103	1	3.521E-03	742	1	5.358E-03
54	738	2	4.903E-03	1587	2	6.970E-03	2035	1	5.838E-03	1296	1	3.509E-03	555	1	5.294E-03
55	1296	1	4.903E-03	226	2	6.814E-03	78	1	5.838E-03	735	1	3.505E-03	536	1	5.271E-03
56	730	1	4.903E-03	232	3	6.814E-03	1496	1	5.838E-03	733	1	3.462E-03	1215	1	5.258E-03

Table 4.2 Prioritized repair order at Northridge earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
57	735	1	4.903E-03	857	1	6.562E-03	454	1	5.838E-03	1823	1	3.396E-03	95	1	5.192E-03
58	733	1	4.903E-03	1890	1	6.469E-03	1457	1	5.838E-03	1933	1	3.362E-03	1857	1	5.189E-03
59	743	1	4.903E-03	1884	1	6.469E-03	681	1	5.838E-03	743	1	3.315E-03	1747	1	5.150E-03
60	1233	2	4.903E-03	1880	1	6.469E-03	751	1	5.838E-03	1839	1	3.301E-03	152	1	5.105E-03
61	724	1	4.903E-03	533	1	6.105E-03	122	1	5.838E-03	681	1	3.301E-03	700	1	5.103E-03
62	723	1	4.903E-03	537	1	6.105E-03	1823	1	5.838E-03	1912	2	3.257E-03	1522	1	5.066E-03
63	725	1	4.903E-03	536	1	6.105E-03	525	1	5.838E-03	294	2	3.135E-03	1839	1	4.997E-03
64	732	1	4.903E-03	525	1	6.105E-03	72	1	5.838E-03	295	2	3.135E-03	103	1	4.940E-03
65	1268	1	4.903E-03	534	1	6.105E-03	2170	1	5.838E-03	724	1	3.128E-03	2035	1	4.902E-03
66	699	1	4.903E-03	544	2	6.105E-03	534	1	5.838E-03	699	1	3.102E-03	78	1	4.733E-03
67	1852	1	4.903E-03	530	2	6.105E-03	2460	1	5.838E-03	137	2	3.085E-03	1496	1	4.730E-03
68	1229	2	4.903E-03	1830	1	5.945E-03	106	1	5.838E-03	1512	2	3.085E-03	454	1	4.707E-03
69	1853	1	4.903E-03	1839	1	5.945E-03	1880	1	5.838E-03	466	1	3.082E-03	1457	1	4.667E-03
70	1884	1	4.903E-03	1709	1	5.302E-03	937	1	5.838E-03	857	1	2.983E-03	681	1	4.628E-03
71	742	1	4.903E-03	555	1	5.207E-03	1478	1	5.838E-03	963	1	2.983E-03	751	1	4.600E-03
72	1215	1	4.903E-03	963	1	5.182E-03	1508	1	5.838E-03	1433	1	2.978E-03	122	1	4.594E-03
73	1857	1	4.903E-03	1188	1	4.932E-03	1916	1	5.838E-03	1721	1	2.961E-03	1823	1	4.568E-03
74	1747	1	4.903E-03	1184	1	4.932E-03	636	1	5.838E-03	135	2	2.961E-03	136	2	4.499E-03
75	152	1	4.903E-03	1204	3	4.932E-03	767	1	5.838E-03	822	2	2.938E-03	294	2	4.469E-03
76	700	1	4.903E-03	1205	3	4.932E-03	1933	1	5.838E-03	1471	2	2.916E-03	295	2	4.469E-03
77	1522	1	4.903E-03	1185	3	4.932E-03	278	1	5.838E-03	723	1	2.899E-03	525	1	4.454E-03
78	1839	1	4.903E-03	1190	2	4.932E-03	466	1	5.838E-03	2460	1	2.895E-03	72	1	4.440E-03
79	1457	1	4.903E-03	1202	2	4.932E-03	139	1	5.838E-03	264	2	2.874E-03	739	2	4.427E-03
80	681	1	4.903E-03	1201	3	4.932E-03	1433	1	5.838E-03	265	2	2.874E-03	2170	1	4.422E-03
81	751	1	4.903E-03	136	2	4.792E-03	1577	2	4.246E-03	2035	1	2.842E-03	534	1	4.404E-03
82	1823	1	4.903E-03	137	2	4.792E-03	1449	2	4.246E-03	725	1	2.832E-03	1586	2	4.392E-03
83	136	2	4.903E-03	135	2	4.792E-03	1426	2	4.246E-03	1867	2	2.818E-03	2460	1	4.378E-03
84	525	1	4.903E-03	138	2	4.792E-03	1998	2	4.246E-03	1520	3	2.800E-03	106	1	4.377E-03
85	2170	1	4.903E-03	128	2	4.792E-03	1255	2	4.246E-03	555	1	2.777E-03	696	2	4.375E-03
86	534	1	4.903E-03	129	2	4.792E-03	738	2	4.246E-03	1926	2	2.752E-03	1880	1	4.365E-03
87	1586	2	4.903E-03	126	2	4.792E-03	1233	2	4.246E-03	732	1	2.733E-03	822	2	4.328E-03
88	106	1	4.903E-03	125	2	4.792E-03	1501	2	4.246E-03	1215	1	2.725E-03	1800	2	4.323E-03
89	1880	1	4.903E-03	130	3	4.792E-03	1256	2	4.246E-03	1441	2	2.549E-03	1809	2	4.323E-03
90	937	1	4.903E-03	134	3	4.792E-03	1229	2	4.246E-03	1442	2	2.549E-03	937	1	4.319E-03
91	137	2	4.903E-03	1537	1	4.744E-03	136	2	4.246E-03	1522	1	2.526E-03	1478	1	4.273E-03
92	135	2	4.903E-03	1532	3	4.744E-03	294	2	4.246E-03	636	1	2.481E-03	1867	2	4.269E-03
93	150	2	4.903E-03	1560	2	4.744E-03	295	2	4.246E-03	1504	1	2.465E-03	1508	1	4.257E-03
94	1916	1	4.903E-03	1533	2	4.744E-03	739	2	4.246E-03	1857	1	2.454E-03	137	2	4.257E-03
95	636	1	4.903E-03	937	1	4.719E-03	1586	2	4.246E-03	1233	2	2.427E-03	135	2	4.225E-03
96	767	1	4.903E-03	681	1	4.471E-03	696	2	4.246E-03	2191	2	2.420E-03	1284	2	4.209E-03
97	1933	1	4.903E-03	693	2	4.471E-03	822	2	4.246E-03	1458	2	2.393E-03	1512	2	4.195E-03
98	278	1	4.903E-03	682	2	4.471E-03	1800	2	4.246E-03	78	1	2.376E-03	1204	3	4.163E-03
99	466	1	4.903E-03	683	2	4.471E-03	1809	2	4.246E-03	1476	2	2.272E-03	150	2	4.123E-03
100	138	2	4.903E-03	686	2	4.471E-03	1867	2	4.246E-03	696	2	2.244E-03	709	2	4.104E-03
101	128	2	4.903E-03	692	3	4.471E-03	137	2	4.246E-03	1503	2	2.233E-03	1916	1	4.081E-03
102	129	2	4.903E-03	691	3	4.471E-03	135	2	4.246E-03	1467	2	2.171E-03	1205	3	4.080E-03
103	1185	3	4.903E-03	689	3	4.471E-03	1284	2	4.246E-03	19	2	2.151E-03	727	2	4.053E-03
104	139	1	4.903E-03	690	3	4.471E-03	1512	2	4.246E-03	122	1	2.138E-03	706	2	4.049E-03
105	1433	1	4.903E-03	1496	1	4.301E-03	150	2	4.246E-03	95	1	2.078E-03	636	1	4.021E-03
106	96	2	4.903E-03	1495	3	4.301E-03	709	2	4.246E-03	739	2	1.974E-03	93	2	4.011E-03
107	1918	2	4.903E-03	1493	3	4.301E-03	727	2	4.246E-03	530	2	1.920E-03	715	2	3.965E-03
108	1495	3	4.903E-03	1486	3	4.301E-03	706	2	4.246E-03	937	1	1.815E-03	286	2	3.880E-03
109	1912	2	4.903E-03	1492	3	4.301E-03	93	2	4.246E-03	1268	1	1.799E-03	710	2	3.875E-03
110	1177	3	4.903E-03	1499	2	4.279E-03	715	2	4.246E-03	536	1	1.784E-03	296	2	3.820E-03
111	104	3	4.903E-03	1498	2	4.279E-03	286	2	4.246E-03	693	2	1.749E-03	1289	3	3.781E-03
112	94	3	4.903E-03	1497	3	4.279E-03	710	2	4.246E-03	1227	1	1.682E-03	767	1	3.779E-03

Table 4.2 Prioritized repair order at Northridge earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
113	92	3	4.903E-03	264	2	4.206E-03	296	2	4.246E-03	742	1	1.653E-03	1214	2	3.746E-03
114	544	2	3.677E-03	265	2	4.206E-03	1214	2	4.246E-03	1185	3	1.645E-03	544	2	3.734E-03
115	1463	2	3.677E-03	252	2	4.206E-03	544	2	4.246E-03	83	2	1.617E-03	1933	1	3.688E-03
116	2191	2	3.677E-03	248	2	4.206E-03	530	2	4.246E-03	102	2	1.604E-03	278	1	3.686E-03
117	1499	2	3.677E-03	263	3	4.206E-03	138	2	4.246E-03	1229	2	1.567E-03	530	2	3.681E-03
118	787	2	3.677E-03	259	3	4.206E-03	1515	2	4.246E-03	1468	2	1.511E-03	466	1	3.676E-03
119	1503	2	3.677E-03	787	2	4.137E-03	128	2	4.246E-03	1493	3	1.483E-03	138	2	3.665E-03
120	1498	2	3.677E-03	1823	1	4.136E-03	129	2	4.246E-03	139	1	1.476E-03	1515	2	3.663E-03
121	102	2	3.677E-03	1800	2	4.136E-03	1463	2	4.246E-03	1586	2	1.450E-03	128	2	3.656E-03
122	100	2	3.677E-03	1809	2	4.136E-03	2191	2	4.246E-03	1496	1	1.424E-03	129	2	3.656E-03
123	101	2	3.677E-03	1822	2	4.136E-03	1587	2	4.246E-03	100	2	1.423E-03	1185	3	3.623E-03
124	115	2	3.677E-03	1747	1	4.110E-03	226	2	4.246E-03	93	2	1.396E-03	1520	3	3.611E-03
125	1471	2	3.677E-03	2191	2	3.945E-03	264	2	4.246E-03	682	2	1.384E-03	1463	2	3.599E-03
126	65	2	3.677E-03	751	1	3.799E-03	265	2	4.246E-03	1448	2	1.359E-03	139	1	3.582E-03
127	74	2	3.677E-03	767	1	3.799E-03	70	2	4.246E-03	1499	2	1.357E-03	2191	2	3.572E-03
128	1532	3	3.269E-03	754	2	3.799E-03	1499	2	4.246E-03	1478	1	1.342E-03	1587	2	3.532E-03
129	1204	3	3.269E-03	286	2	3.681E-03	96	2	4.246E-03	252	2	1.331E-03	226	2	3.530E-03
130	1205	3	3.269E-03	278	1	3.681E-03	1918	2	4.246E-03	248	2	1.274E-03	1433	1	3.451E-03
131	1493	3	3.269E-03	279	2	3.681E-03	787	2	4.246E-03	754	2	1.234E-03	264	2	3.444E-03
132	1486	3	3.269E-03	1998	2	3.287E-03	693	2	4.246E-03	1508	1	1.233E-03	265	2	3.444E-03
133	1492	3	3.269E-03	293	1	3.142E-03	1912	2	4.246E-03	683	2	1.221E-03	70	2	3.394E-03
134	98	3	3.269E-03	294	2	3.142E-03	1190	2	4.246E-03	1190	2	1.212E-03	1499	2	3.390E-03
135	97	3	3.269E-03	295	2	3.142E-03	1202	2	4.246E-03	1427	2	1.167E-03	1574	3	3.378E-03
136	1907	3	3.269E-03	296	2	3.142E-03	1503	2	4.246E-03	709	2	1.158E-03	711	3	3.370E-03
137	1256	2	2.451E-03	99	1	3.047E-03	1498	2	4.246E-03	96	2	1.155E-03	708	3	3.367E-03
138	739	2	2.451E-03	95	1	3.047E-03	102	2	4.246E-03	1289	3	1.137E-03	705	3	3.359E-03
139	696	2	2.451E-03	103	1	3.047E-03	682	2	4.246E-03	98	3	1.137E-03	96	2	3.338E-03
140	1800	2	2.451E-03	122	1	3.047E-03	100	2	4.246E-03	1202	2	1.133E-03	1918	2	3.291E-03
141	1809	2	2.451E-03	106	1	3.047E-03	683	2	4.246E-03	105	2	1.128E-03	1495	3	3.240E-03
142	1867	2	2.451E-03	93	2	3.047E-03	126	2	4.246E-03	101	2	1.117E-03	787	2	3.232E-03
143	1284	2	2.451E-03	96	2	3.047E-03	252	2	4.246E-03	700	1	1.111E-03	693	2	3.229E-03
144	1512	2	2.451E-03	102	2	3.047E-03	248	2	4.246E-03	1177	3	1.078E-03	1912	2	3.211E-03
145	709	2	2.451E-03	100	2	3.047E-03	125	2	4.246E-03	70	2	1.062E-03	1190	2	3.210E-03
146	727	2	2.451E-03	101	2	3.047E-03	101	2	4.246E-03	1907	3	1.042E-03	741	4	3.207E-03
147	706	2	2.451E-03	115	2	3.047E-03	1560	2	4.246E-03	525	1	9.709E-04	1202	2	3.191E-03
148	715	2	2.451E-03	104	3	3.047E-03	115	2	4.246E-03	1515	2	9.578E-04	1503	2	3.190E-03
149	710	2	2.451E-03	94	3	3.047E-03	1822	2	4.246E-03	155	2	9.485E-04	1498	2	3.176E-03
150	1214	2	2.451E-03	92	3	3.047E-03	1533	2	4.246E-03	706	2	9.383E-04	102	2	3.143E-03
151	530	2	2.451E-03	105	2	3.047E-03	754	2	4.246E-03	1822	2	9.268E-04	682	2	3.138E-03
152	1515	2	2.451E-03	98	3	3.047E-03	1476	2	4.246E-03	544	2	9.088E-04	714	4	3.098E-03
153	1587	2	2.451E-03	97	3	3.047E-03	686	2	4.246E-03	115	2	8.933E-04	100	2	3.098E-03
154	226	2	2.451E-03	120	4	3.047E-03	1471	2	4.246E-03	787	2	8.691E-04	683	2	3.098E-03
155	264	2	2.451E-03	118	4	3.047E-03	105	2	4.246E-03	1284	2	7.976E-04	713	4	3.074E-03
156	265	2	2.451E-03	636	1	2.862E-03	279	2	4.246E-03	126	2	7.900E-04	126	2	3.070E-03
157	1574	3	2.451E-03	825	1	2.771E-03	1458	2	4.246E-03	534	1	7.695E-04	1521	3	3.069E-03
158	693	2	2.451E-03	822	2	2.771E-03	1467	2	4.246E-03	1456	3	7.657E-04	252	2	3.059E-03
159	1190	2	2.451E-03	2185	1	2.721E-03	1926	2	4.246E-03	1459	3	7.657E-04	248	2	3.044E-03
160	1202	2	2.451E-03	2170	1	2.721E-03	1441	2	4.246E-03	1495	3	7.444E-04	125	2	3.026E-03
161	682	2	2.451E-03	1177	3	2.669E-03	1442	2	4.246E-03	65	2	7.253E-04	101	2	3.022E-03
162	683	2	2.451E-03	1176	3	2.669E-03	1468	2	4.246E-03	138	2	7.184E-04	1560	2	3.021E-03
163	126	2	2.451E-03	1504	1	2.604E-03	155	2	4.246E-03	1214	2	7.179E-04	1493	3	3.016E-03
164	252	2	2.451E-03	1501	2	2.604E-03	65	2	4.246E-03	1486	3	7.160E-04	115	2	2.966E-03
165	248	2	2.451E-03	1508	1	2.604E-03	74	2	4.246E-03	1574	3	6.941E-04	1822	2	2.940E-03
166	125	2	2.451E-03	1503	2	2.604E-03	19	2	4.246E-03	128	2	6.852E-04	1533	2	2.937E-03
167	1560	2	2.451E-03	1478	1	2.557E-03	1448	2	4.246E-03	129	2	6.852E-04	754	2	2.933E-03
168	1822	2	2.451E-03	1476	2	2.557E-03	83	2	4.246E-03	1896	3	6.797E-04	1177	3	2.916E-03

Table 4.2 Prioritized repair order at Northridge earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
169	1533	2	2.451E-03	1484	4	2.557E-03	1427	2	4.246E-03	1560	2	6.421E-04	232	3	2.890E-03
170	754	2	2.451E-03	1483	4	2.557E-03	1532	3	3.013E-03	1521	3	6.316E-04	1476	2	2.882E-03
171	1476	2	2.451E-03	152	1	2.110E-03	1204	3	3.013E-03	125	2	6.164E-04	686	2	2.867E-03
172	686	2	2.451E-03	150	2	2.110E-03	1205	3	3.013E-03	226	2	6.084E-04	104	3	2.857E-03
173	105	2	2.451E-03	139	1	2.110E-03	1289	3	3.013E-03	767	1	5.747E-04	1486	3	2.825E-03
174	279	2	2.451E-03	155	2	2.110E-03	1185	3	3.013E-03	296	2	5.366E-04	94	3	2.801E-03
175	1458	2	2.451E-03	156	3	2.110E-03	1520	3	3.013E-03	130	3	5.360E-04	1471	2	2.769E-03
176	1467	2	2.451E-03	146	3	2.110E-03	1574	3	3.013E-03	1498	2	5.021E-04	92	3	2.759E-03
177	1926	2	2.451E-03	178	3	1.604E-03	711	3	3.013E-03	727	2	4.772E-04	1492	3	2.734E-03
178	1441	2	2.451E-03	1113	1	1.574E-03	708	3	3.013E-03	104	3	4.646E-04	105	2	2.718E-03
179	1442	2	2.451E-03	1460	1	1.548E-03	705	3	3.013E-03	1587	2	4.614E-04	279	2	2.680E-03
180	1497	3	2.451E-03	1449	2	1.548E-03	1495	3	3.013E-03	74	2	4.211E-04	1458	2	2.659E-03
181	1468	2	2.451E-03	1457	1	1.548E-03	1521	3	3.013E-03	1176	3	4.087E-04	98	3	2.616E-03
182	155	2	2.451E-03	1463	2	1.548E-03	1493	3	3.013E-03	1201	3	3.705E-04	1467	2	2.604E-03
183	19	2	2.451E-03	1458	2	1.548E-03	1177	3	3.013E-03	178	3	3.573E-04	1926	2	2.524E-03
184	1448	2	2.451E-03	1467	2	1.548E-03	232	3	3.013E-03	1492	3	3.546E-04	130	3	2.494E-03
185	83	2	2.451E-03	1468	2	1.548E-03	104	3	3.013E-03	279	2	3.396E-04	1441	2	2.490E-03
186	1427	2	2.451E-03	1456	3	1.548E-03	1486	3	3.013E-03	692	3	3.258E-04	1442	2	2.490E-03
187	1484	4	2.451E-03	1459	3	1.548E-03	94	3	3.013E-03	278	1	3.229E-04	1201	3	2.488E-03
188	178	3	2.451E-03	1455	3	1.548E-03	92	3	3.013E-03	263	3	3.188E-04	1497	3	2.460E-03
189	64	3	2.451E-03	1465	4	1.548E-03	1492	3	3.013E-03	1533	2	3.077E-04	1468	2	2.439E-03
190	1465	4	1.839E-03	1466	4	1.548E-03	98	3	3.013E-03	97	3	3.073E-04	155	2	2.439E-03
191	1289	3	1.634E-03	2460	1	1.423E-03	130	3	3.013E-03	691	3	3.032E-04	134	3	2.433E-03
192	1520	3	1.634E-03	2035	1	1.122E-03	1201	3	3.013E-03	686	2	3.012E-04	97	3	2.409E-03
193	711	3	1.634E-03	75	1	9.131E-04	1497	3	3.013E-03	689	3	2.925E-04	65	2	2.390E-03
194	708	3	1.634E-03	78	1	9.131E-04	134	3	3.013E-03	134	3	2.908E-04	692	3	2.361E-03
195	705	3	1.634E-03	72	1	9.131E-04	97	3	3.013E-03	711	3	2.725E-04	691	3	2.356E-03
196	1521	3	1.634E-03	70	2	9.131E-04	692	3	3.013E-03	708	3	2.589E-04	689	3	2.353E-03
197	232	3	1.634E-03	65	2	9.131E-04	691	3	3.013E-03	1880	1	2.506E-04	74	2	2.314E-03
198	130	3	1.634E-03	74	2	9.131E-04	689	3	3.013E-03	710	2	2.442E-04	690	3	2.301E-03
199	1201	3	1.634E-03	64	3	9.131E-04	690	3	3.013E-03	94	3	2.412E-04	263	3	2.293E-03
200	134	3	1.634E-03	455	1	8.825E-04	263	3	3.013E-03	286	2	2.390E-04	19	2	2.270E-03
201	692	3	1.634E-03	454	1	8.825E-04	259	3	3.013E-03	705	3	2.282E-04	259	3	2.248E-03
202	691	3	1.634E-03	466	1	8.825E-04	1907	3	3.013E-03	1902	3	2.233E-04	1448	2	2.193E-03
203	689	3	1.634E-03	1441	2	7.139E-04	1176	3	3.013E-03	1483	4	1.804E-04	83	2	2.119E-03
204	690	3	1.634E-03	1442	2	7.139E-04	178	3	3.013E-03	1466	4	1.737E-04	1427	2	1.987E-03
205	263	3	1.634E-03	1448	2	7.139E-04	1456	3	3.013E-03	1455	3	1.581E-04	1907	3	1.941E-03
206	259	3	1.634E-03	1933	1	6.478E-04	1459	3	3.013E-03	259	3	1.396E-04	1176	3	1.931E-03
207	1176	3	1.634E-03	1926	2	6.478E-04	156	3	3.013E-03	156	3	1.343E-04	1484	4	1.887E-03
208	1456	3	1.634E-03	1925	3	6.478E-04	146	3	3.013E-03	1925	3	1.319E-04	178	3	1.856E-03
209	1459	3	1.634E-03	1919	1	4.396E-04	64	3	3.013E-03	715	2	1.254E-04	1456	3	1.740E-03
210	156	3	1.634E-03	1913	1	4.396E-04	1455	3	3.013E-03	1465	4	1.231E-04	1459	3	1.740E-03
211	146	3	1.634E-03	1916	1	4.396E-04	1896	3	3.013E-03	146	3	1.226E-04	156	3	1.723E-03
212	1455	3	1.634E-03	1918	2	4.396E-04	1925	3	3.013E-03	714	4	1.167E-04	146	3	1.720E-03
213	1896	3	1.634E-03	1912	2	4.396E-04	1902	3	3.013E-03	232	3	1.004E-04	120	4	1.707E-03
214	1925	3	1.634E-03	1907	3	4.396E-04	741	4	2.491E-03	1497	3	9.730E-05	118	4	1.699E-03
215	1902	3	1.634E-03	1896	3	4.396E-04	714	4	2.491E-03	690	3	8.613E-05	1483	4	1.614E-03
216	741	4	1.226E-03	1902	3	4.396E-04	713	4	2.491E-03	741	4	7.701E-05	64	3	1.609E-03
217	714	4	1.226E-03	1471	2	2.375E-04	1484	4	2.491E-03	92	3	7.382E-05	1455	3	1.588E-03
218	713	4	1.226E-03	19	2	2.328E-04	120	4	2.491E-03	120	4	6.415E-05	1465	4	1.500E-03
219	120	4	1.226E-03	83	2	1.629E-04	118	4	2.491E-03	64	3	5.764E-05	1896	3	1.442E-03
220	118	4	1.226E-03	1426	2	8.351E-05	1483	4	2.491E-03	1484	4	4.785E-05	1466	4	1.360E-03
221	1483	4	1.226E-03	1433	1	8.351E-05	1465	4	2.491E-03	118	4	3.252E-05	1925	3	1.357E-03
222	1466	4	1.226E-03	1427	2	8.351E-05	1466	4	2.491E-03	713	4	1.885E-05	1902	3	1.328E-03

And, the spatial distributions of those repair orders are depicted on maps of highway network model shown in Figure 4.5 to Figure 4.9. The priority values of each alternative (i.e., damaged bridges) are calculated on the basis of pairwise comparison of weight values as described in section 3.2. In addition to these five repair processes, the simultaneous repair scenario is also analyzed. This scenario is assumed that all reconstruction works of damaged bridges will be started simultaneously from Day 0. Therefore, the unlimited regional labor (i.e., necessary labor for all bridges' repair work) is applied to this simulation case.

Transportation network analysis is then performed according to progress of bridge damage repairing and traffic demand recovering at every certain time until the network restitutes to the pre-earthquake condition, and a restoration curve is obtained as a result. The bridge restoration curves (i.e., physical recovery of highway network) of three bridge restoration models are shown in Figure 4.33 to Figure 4.35, respectively, and social loss restoration curves (i.e., performance recovery of highway network) corresponding to each bridge restoration models are illustrated in Figure 4.36 to Figure 4.38, respectively. These results are the mean value of 400 times of Monte Carlo Simulation, and the integration value from Day 0 to the completion date represents total performance loss due to the earthquake during the entire restoration process. This total performance loss is converted from time loss to economic loss and is compared with other cases' results in monetary value after adding total bridge repair cost.

Both bridge restoration and social loss restoration proceed on entirely different paths depending on bridge restoration models, Markov Chain process model, Uniform distribution model and Normal distribution model. With respect to bridge restoration, the earliest recovery progress is simulated by Normal distribution model and the slowest one is represented by Uniform distribution model. The recovery progress by Markov Chain process model locates at intermediate position between other two paths. The trend that the importance priority makes bridge recovery slowly is common to all restoration models. As for social loss restoration, the curve shape of each restoration model is similar to the shape of corresponding bridge restoration curve except for Markov Chain process model. The social restoration curves of this model are intersected and complicated as compared to its bridge restoration curves, and this complex processes seem to reflect a practical work progress. The social loss restoration by this model is the earliest recovery of all bridge models. A parallel between three models about social restoration curves is that the importance priority stimulates the recovery of highway performance in spite of its slow restoration of damaged bridges. Thus, the traffic performance (i.e., social loss) recovery curves are obviously different depending on bridge restoration model though repair orders of each criterion are the same in three models. Therefore, the applicability verification of Markov Chain process model is meaningful for accuracy of restoration simulation.

Bridge restoration passages other than importance priority are expressed by the almost same curve shape, and this is common finding in three bridge models. The bridge recovery of importance priority requires longer time and slower advancement compared to other priorities. This means that the repair order based on importance criterion is not an efficient sequence in the sense of physical recovery. On the other hand, social loss restoration curves of importance priority simulated by each restoration models are almost same as other priorities' processes, and there are not so big differences about completion date between all priorities. Specifically, the performance recovery of Markov Chain process model along importance priority is faster than that of difficulty priority and mix priority until the half of restoration period though the bridge reconstruction work of importance priority is much slower than other priorities. This tendency suggests that the importance priority can facilitate highway performance recovery effectively in comparison with other prioritization criteria. Thus, traffic performance restorations also change significantly according to repair orders especially in Markov Chain process model.

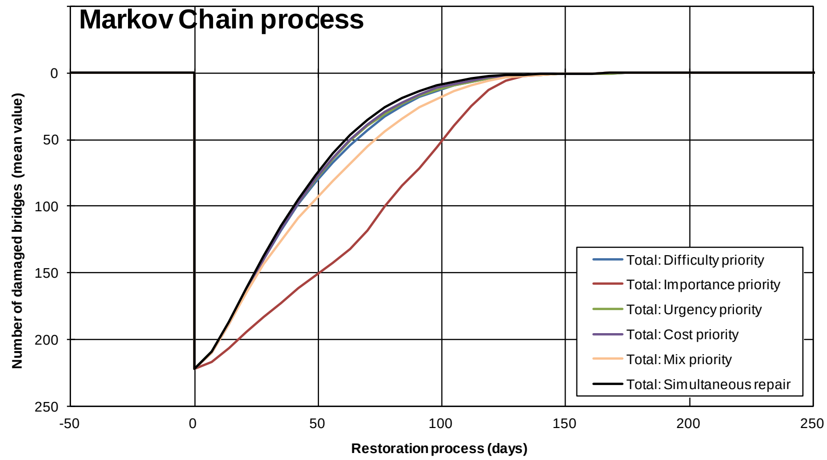


Figure 4.33 Bridge restoration curve: Markov Chain process model (Moderate).

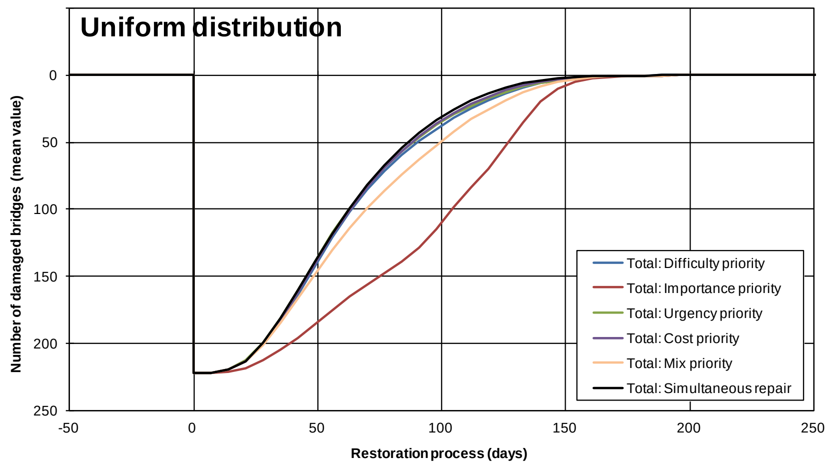


Figure 4.34 Bridge restoration curve: Uniform distribution model (Moderate).

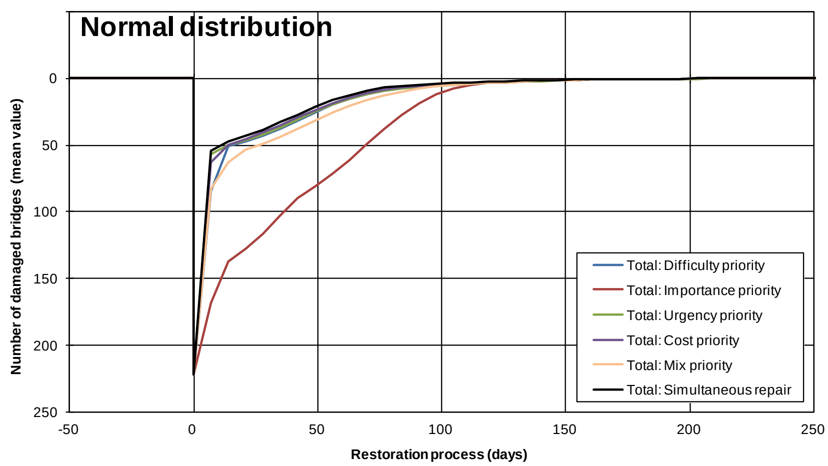


Figure 4.35 Bridge restoration curve: Normal distribution model (Moderate).

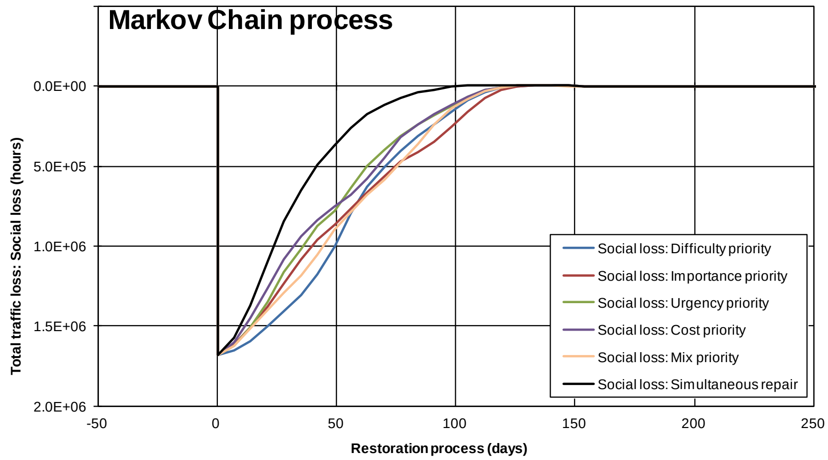


Figure 4.36 Social loss restoration curve: Markov Chain process model (Moderate).

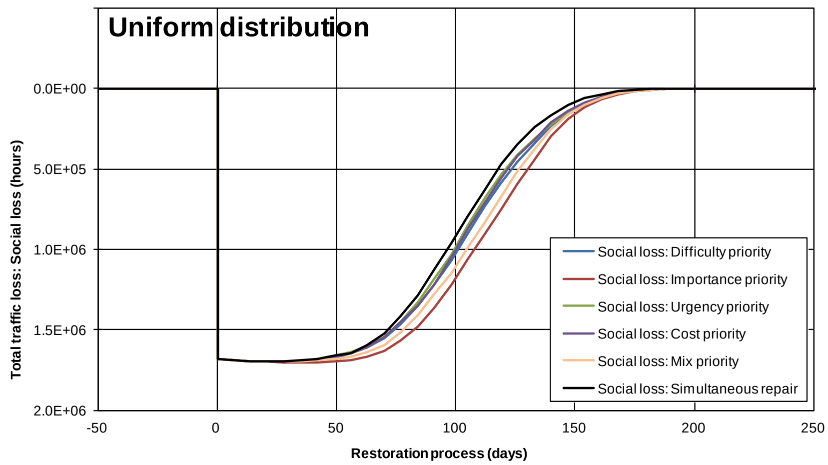


Figure 4.37 Social loss restoration curve: Uniform distribution model (Moderate).

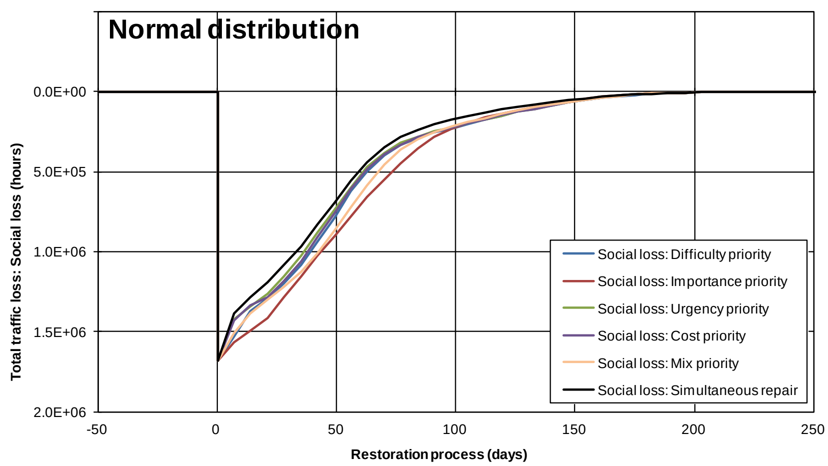


Figure 4.38 Social loss restoration curve: Normal distribution model (Moderate).

The economic value of total social loss is converted from time unit (i.e., hours) by applying the averaged unit cost of drivers' time described in section 2.8 and is represented by 2012 U.S. dollars in this study. The total economic losses including total bridge repair cost estimated by three bridge restoration models and six prioritized repair orders are shown in Figure 4.39 to Figure 4.41. The total economic loss of Markov Chain process model is the smallest in three bridge restoration models, averagely. And, the total economic loss of Normal distribution model is a little more than that of Markov Chain process model. On the contrary, the total economic loss of Uniform distribution model is more than double for that of Markov Chain process model. As described in sections about restoration curve estimation, this large difference is mainly induced by conservative restoration process simulated through Uniform distribution model. Now, there cannot be recognized any major gaps between each economic losses based on six priorities in Normal distribution model and Uniform distribution model, and the largest gap is about 20% between importance priority and simultaneous repair. At the same time, the biggest difference in Markov Chain process model is more than 70%, and it is between difficulty priority (about 1.60 billion dollars) and simultaneous repair (about 0.92 billion dollars). It is reasonable result that the restoration process under simultaneous repair (i.e., unlimited regional labor) causes the smallest social loss and its total amount is much less than other priorities' losses. The smallest economic loss is cost priority next to simultaneous repair in Markov Chain process model, and its difference is 1.45 times and about 0.41 billion dollars. The largest economic loss is induced by difficulty priority, and its difference from cost priority is 1.20 times and about 0.27 billion dollars. As well as the results of social loss restoration curves, Markov Chain process model is considered to be able to reflect a realistic aspects corresponding to priorities to the results of total economic loss. Thus, the total economic loss is also changing drastically corresponding to the bridge restoration model and the prioritization of repair order so the verification of Markov Chain process model is also fruitful for economic loss assessment.

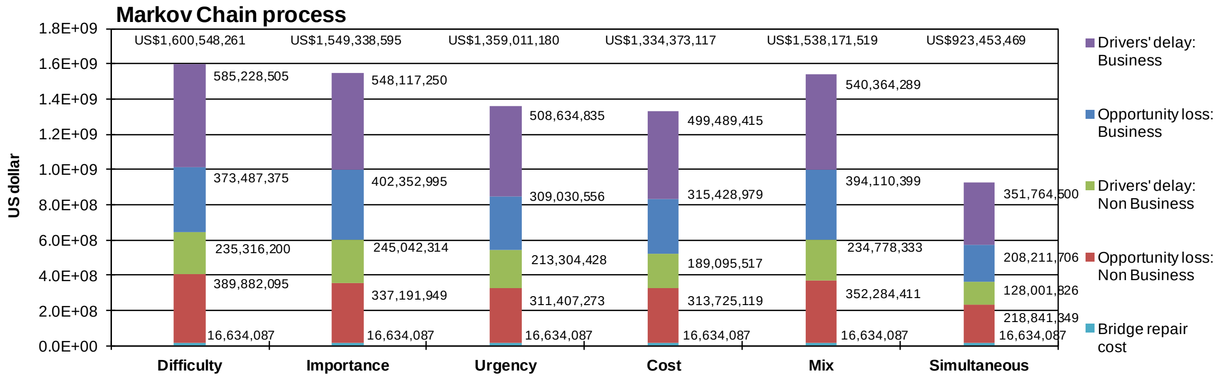


Figure 4.39 Monetary value of social loss: Markov Chain process model (Moderate).

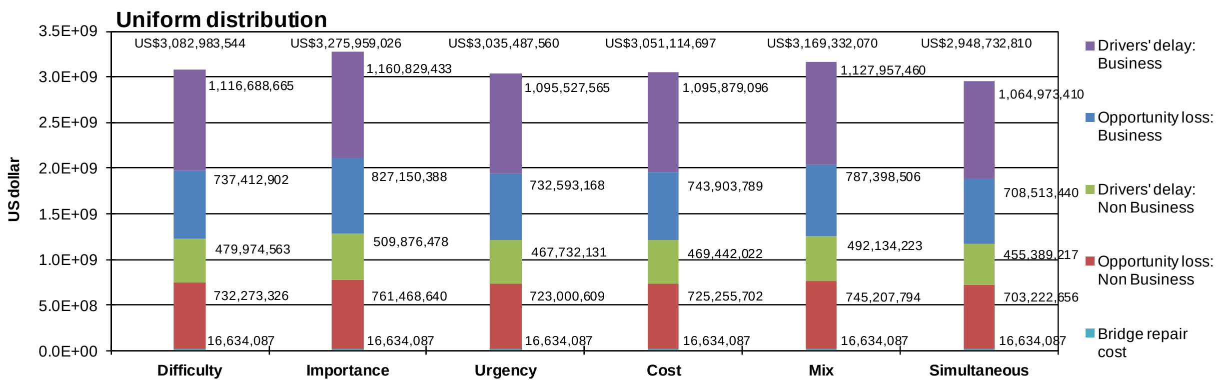


Figure 4.40 Monetary value of social loss: Uniform distribution model (Moderate).

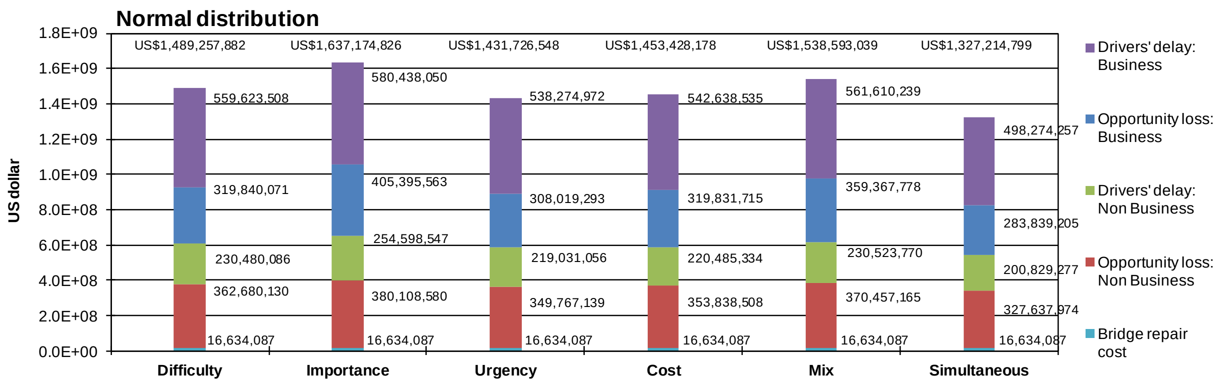


Figure 4.41 Monetary value of social loss: Normal distribution model (Moderate).

Chapter 5

Scenario earthquake application

As an application example of the developed probabilistic methodology for post-earthquake restoration process of highway network system, a regional potential scenario earthquake is applied to the established model and an entire simulation is made through the whole algorithms. Newport-Inglewood fault earthquake Mw7.1, one of 63 regional seismic hazards described in section 2.2.2, is utilized as a scenario earthquake for this application example because the expected damage caused by this earthquake is supposed to be tremendous (Zhou, 2006). In addition, a post-earthquake simulation for an earthquake occurring directly beneath Los Angeles metropolitan area provides a powerful lens and a useful opportunity for thinking about seismic damage mitigation and enhancement of highway network resilience for this target region. This pilot study is conducted by following the analysis flow as shown in Figure 5.1. More specifically, bridge damage state is identified at the first step based on bridge fragility shown in Figure 2.4 and PGA distribution of Newport-Inglewood scenario earthquake illustrated in Figure 2.3. Bridge damage states are then reflected to damage state and residual traffic capacity of corresponding links. Repair orders are decided on both bridge damage status and several priority criteria through the prioritization algorithm, Analytic Hierarchy Process. The traffic network analysis is performed under the intact highway situation (i.e., pre-earthquake situation) before post-earthquake analysis for obtaining the baseline vehicle driving time. The simulation of restoration process is then conducted by applying bridge restoration model and traffic demand recovery model, and this simulation is continued with updating recovery status of highway network damage and traffic demand at certain time until the reconstruction works are completed. The time step of restoration process model is 1 week (i.e., 7 days) in this methodology because the bridge restoration model is established based on a condition of renewing damage status every 1 week. Finally, several kinds of restoration curves and total social losses in time and monetary value are obtained for representing detailed post-earthquake restoration passages and seismic impacts to economy. Additionally, three levels of residual traffic capacity are considered for doing sensitivity estimation in this application example. In the last section of this chapter, a way of practical utilization is suggested for effective usage of this methodology by showing detailed result graphs and presenting fine divided estimations.

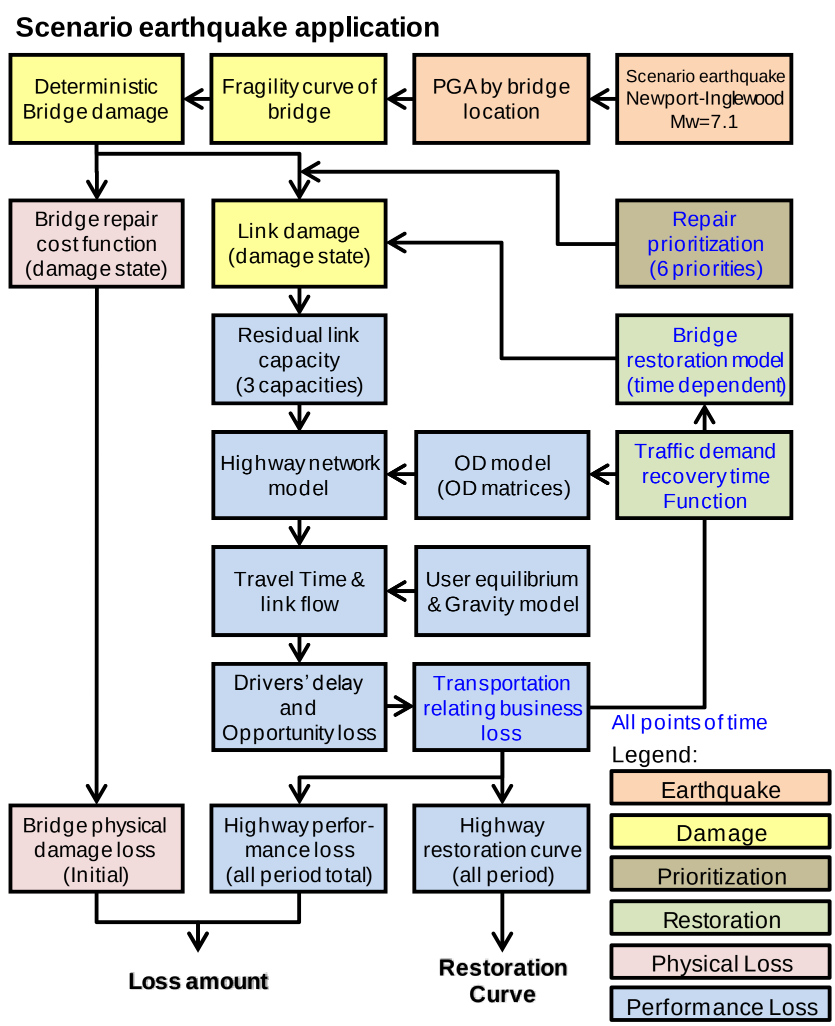


Figure 5.1 Analysis flow of scenario earthquake application.

5.1 Application conditions

The analysis conditions of application example are presented in Figure 5.2. Newport-Inglewood scenario earthquake Mw7.1 is taken to treat as a regional seismic hazard for this application study, and its detailed characteristics and PGA distribution are indicated in section 2.2.2. The bridge damages caused by this earthquake are deterministically assumed by a judgment with consideration of empirical bridge fragility curve and PGA intensity at corresponding bridge site, and the link damage status and the residual traffic capacity rate are subsequently identified based on bridge damage state. Six priority criteria to prioritize bridge repair order are applied, and those are difficulty, importance, urgency, cost, mix and simultaneous repair. 3,000 highway construction workers are assigned as the limited regional labor under the post-earthquake situation to constrain work progress for reflecting actual repair

Initial damage state : Initial bridge damage is identified by PGA and bridge fragility
Repair priority : Difficulty, Importance, Urgency, Cost, Mix and Simultaneous
Limited regional labor : 3,000 (additionally, Unlimited)
Bridge restoration model: Markov Chain process
Residual traffic capacity : Moderate, High and Low (sensitivity analysis)

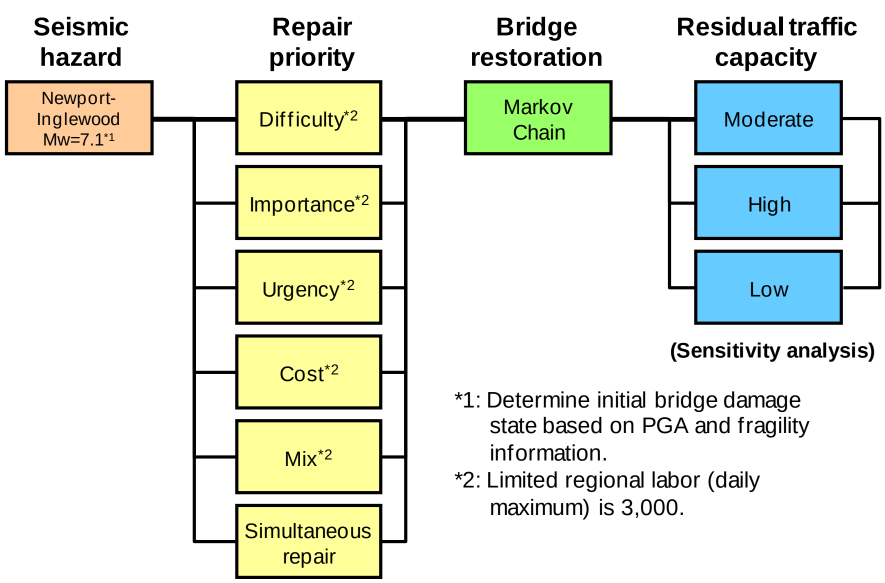


Figure 5.2 Analysis conditions for scenario earthquake application.

circumstance, and the situation of unrestraint labor is also considered to analyze post-earthquake recovery scenario under simultaneous repair. The Markov Chain process model verified in section 4.3.1 is used to simulate the progress of bridge reconstruction work. The moderate level of residual traffic capacity verified in section 4.3.2 is primarily applied to consider decreased traffic capability of damaged link, and the high level and low level of traffic capacity are also used to investigate the sensitivity of post-earthquake highway performance to the residual traffic capacities.

5.2 Initial damage state

The bridge damages induced by Newport-Inglewood scenario earthquake are determined as follows: collapsed bridges are 14, major damaged bridges are 128, moderated damaged bridges are 197, and minor damaged bridges are 185. Therefore, the total number of damaged bridges is 524. The geographical distribution of damaged bridges is depicted in Figure 5.3. In this figure, larger circle indicates severer damage status, and the fault line of this scenario earthquake is also drawn. The more serious damaged bridges are spatially distributed along the fault line in both southern Los Angeles county and western Orange county. When the damaged bridge number is compared, the total of Newport-Inglewood scenario earthquake is more than double of that of Northridge earthquake. Therefore, the performance loss of highway traffic network at Newport-Inglewood scenario earthquake could be more extensive. Corresponding to bridge damage status, the link damages are indentified for all 462 round-trip links. The link damage distribution is illustrated in Figure 5.4. In this figure, several colors are used for expressing link damage states as defined in the map legend and the Newport-Inglewood earthquake fault is also lined. 26 of collapse damage, 114 of major damage, 70 of moderate damage and 46 of minor damage are caused to highway links by this scenario earthquake. Then,

Figure 5.3 Bridge initial damages by Newport-Inglewood earthquake.

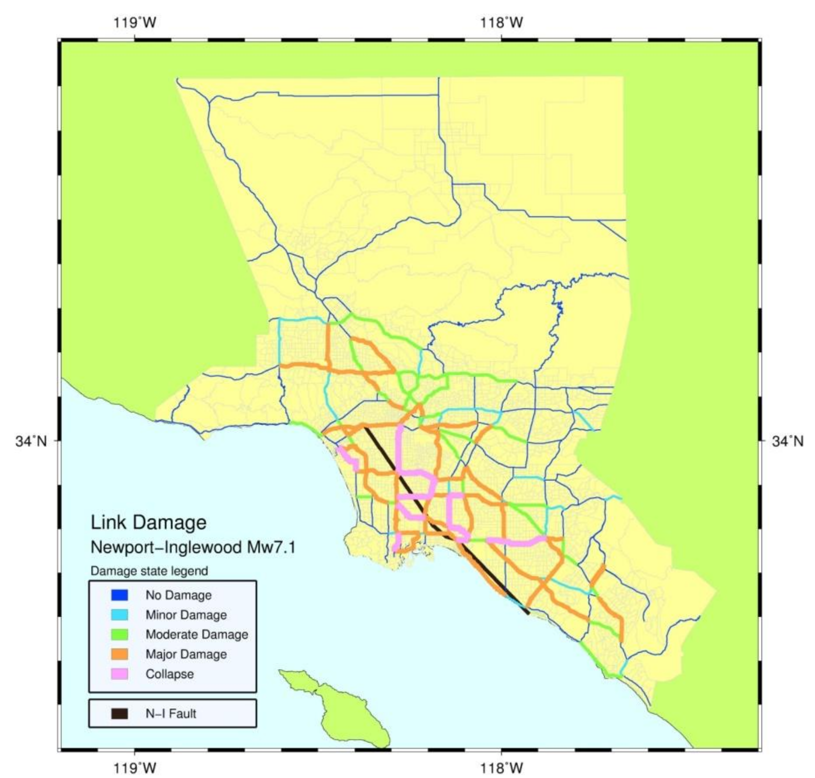


Figure 5.4 Link initial damages by Newport-Inglewood earthquake.

the total number of damaged links is 256. The total number of links which are disrupted traffic capacity is finally estimated as 210 links because the minor damaged link is assumed to be able to keep 100% capacity in this study. The impaired links (i.e., pink, orange and green colored routes) are spread around the fault line as well.

5.3 Prioritized repair order

Bridge repair orders are decided on the basis of five combinations derived from four prioritization criteria in this study. Those priority criteria are difficulty, importance, urgency, cost and mix criterion. Weight values of each alternative in each criterion are defined as a fixed value in section 3.2.2, and weight value between four criteria are changed according to each target prioritization. Sequentially, the weight value of difficulty is 1.0 and the others are 0.0 for difficulty criterion, the weight value of importance is 1.0 and the others are 0.0 for importance criterion, the weight value of urgency is 1.0 and the others are 0.0 for urgency criterion, the weight value of cost is 1.0 and the others are 0.0 for cost criterion, and the weight values of mix criterion are equally 0.25 because four criteria are assigned their priority evenly. The estimated repair orders are then depicted in Figure 5.5 to Figure 5.9, and the fault line of Newport-Inglewood scenario earthquake is also illustrated. In these figures, larger circle denotes earlier repair order, and the bridges repaired within the first 25% order of all damaged bridges are displayed by red and pink color.

The repair orders of five combinations obviously change depending on each criterion such as reconstruction order priority, and reconstruction work progress can be speculated from the distributions of prioritized orders. In difficulty priority, the first 25% of all damaged bridges are distributed almost uniformly throughout the entire damaged area of highway network model as shown in Figure 5.5. This means that the bridges with easier construction work considering bridge scale, soil condition and bridge damage state are sprinkled in the damaged area. Therefore, difficulty priority might be disadvantageous repair priority from the standpoint of efficient construction work progress in distance. If importance criterion is given the most priority to determine the reconstruction order, the damaged bridges in metropolitan area such as downtown Los Angeles, Santa Monica and LAX area are rehabilitated first as expressed in Figure 5.6 because of their heavier traffic volume under pre-earthquake situation. In this case, the loss of continuous reconstruction work in distance (e.g., transfer of construction equipments) is small but the time progress of bridge repair (i.e., physical recovery of highway) may be more slowly than other prioritized orders. In the order prioritized by urgency criterion, the damaged bridges repaired earlier are distributed broadly in the damaged area as illustrated in Figure 5.7, and this trend is similar to the case of difficulty priority. However, the rehabilitation progress in time is supposed to be more rapid than others though there is not particular advantage in distance. This is because the damaged bridges fully repaired in shorter averaged time are prioritized in this criterion. When the bridge repair cost is considered to prioritize reconstruction order, the first 25% of all damaged bridges (i.e., cheaper repair cost) are widely found in the area among Pasadena, Long Beach, Santa Monica and Burbank as shown in Figure 5.8. As a result, the repair order distribution of this criterion is about an intermediate range between difficulty priority and importance priority. Therefore, the loss of continuous reconstruction work in both distance and time is not thought to be significant. If the described four criteria are equally mixed with each other, the prioritized repair order is obtained as drawn in Figure 5.9. The repair order distribution of this mix criterion seems to be decent order based on four repair orders. In addition, the bridge damage distribution is plainly reflected with this repair order because three criteria except for importance criterion are affected in some way by bridge damage status.

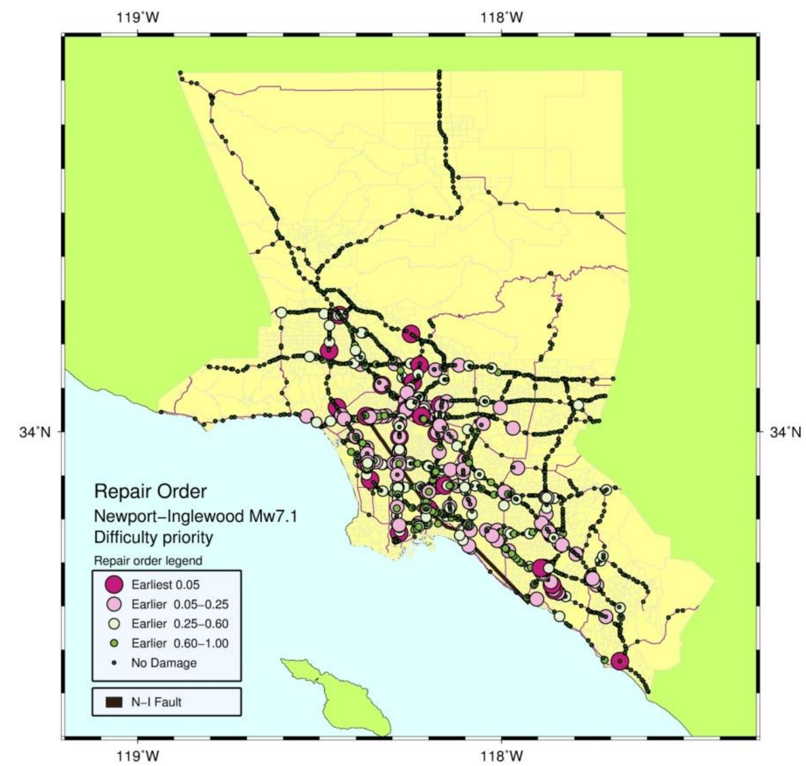


Figure 5.5 Prioritized repair order for Newport-Inglewood earthquake on Difficulty.

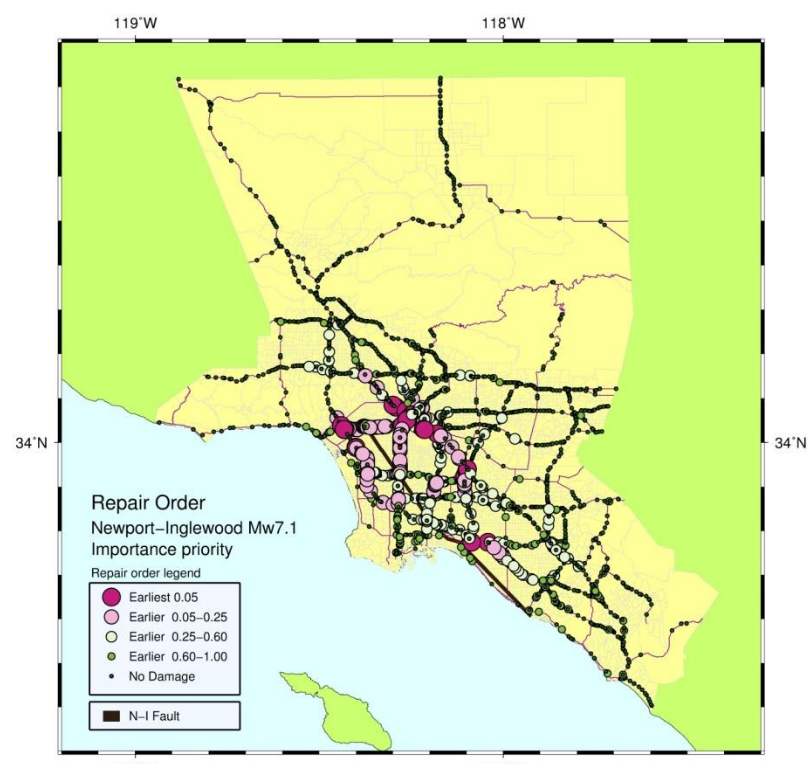


Figure 5.6 Prioritized repair order for Newport-Inglewood earthquake on Importance.

Figure 5.7 Prioritized repair order for Newport-Inglewood earthquake on Urgency.

Figure 5.8 Prioritized repair order for Newport-Inglewood earthquake on Cost.

Figure 5.9 Prioritized repair order for Newport-Inglewood earthquake on Mix priority.

The prioritized orders and the corresponding priority values for all 524 damaged bridges are shown separately with respect to each criterion in Table 5.1, and the priority values of each alternative (i.e., damaged bridges) are calculated by pairwise comparison of weight values through Analytic Hierarchy Process. Since the criteria of difficulty, urgency and cost are affected by bridge damage state to an extent, the bridges suffering slighter damage are prioritized to earlier orders. On the other hand, the repair order by importance priority does not relate to bridge damage state because importance criterion is only based on intact traffic volume of links on which damaged bridges locate. In addition to these five repair orders, the simultaneous repair scenario is studied as well. This scenario is presumed that all reconstruction works of damaged bridges will be started simultaneously right after the earthquake. In other words, the unlimited regional labor (i.e., necessary labor for all bridges' repair work) is applied to this simulation case.

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria.

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
1	1589	1	1.267E-02	1231	2	4.114E-03	1379	1	2.498E-03	1379	1	7.308E-02	1379	1	2.057E-02
2	1973	1	6.335E-03	2882	2	4.090E-03	850	1	2.498E-03	1630	2	3.654E-02	1630	2	1.135E-02
3	543	1	6.335E-03	2875	2	4.090E-03	1756	1	2.498E-03	1692	2	3.248E-02	1692	2	9.753E-03
4	2843	1	6.335E-03	2886	3	4.090E-03	728	1	2.498E-03	2564	2	3.132E-02	2564	2	8.813E-03
5	2842	1	6.335E-03	1254	2	4.069E-03	1973	1	2.498E-03	1756	1	2.627E-02	850	1	8.448E-03
6	2745	1	6.335E-03	1256	1	4.069E-03	1208	1	2.498E-03	850	1	2.570E-02	1756	1	8.416E-03
7	2841	1	6.335E-03	1255	3	4.069E-03	1680	1	2.498E-03	1254	2	2.505E-02	1254	2	8.263E-03
8	1987	1	6.335E-03	1119	2	4.015E-03	1589	1	2.498E-03	1119	2	1.949E-02	728	1	7.134E-03
9	2833	1	6.335E-03	1117	1	4.015E-03	543	1	2.498E-03	1110	2	1.949E-02	1119	2	6.857E-03
10	2756	1	6.335E-03	1630	2	3.890E-03	2200	1	2.498E-03	728	1	1.856E-02	1973	1	6.826E-03
11	1379	1	4.223E-03	1626	1	3.890E-03	738	1	2.498E-03	1973	1	1.772E-02	1208	1	6.422E-03
12	850	1	4.223E-03	1617	1	3.890E-03	457	1	2.498E-03	1208	1	1.624E-02	1680	1	6.152E-03
13	1756	1	4.223E-03	1628	2	3.890E-03	984	1	2.498E-03	1680	1	1.528E-02	1589	1	6.044E-03
14	728	1	4.223E-03	1620	3	3.890E-03	1049	1	2.498E-03	761	2	1.392E-02	543	1	6.006E-03
15	1208	1	4.223E-03	1605	2	3.890E-03	1050	1	2.498E-03	1148	2	1.329E-02	1110	2	5.996E-03
16	1680	1	4.223E-03	491	1	3.882E-03	1948	1	2.498E-03	1670	2	1.309E-02	2200	1	5.156E-03
17	738	1	4.223E-03	497	2	3.882E-03	2210	1	2.498E-03	543	1	1.299E-02	1670	2	4.905E-03
18	984	1	4.223E-03	1265	1	3.588E-03	1184	1	2.498E-03	2200	1	1.299E-02	761	2	4.804E-03
19	1948	1	4.223E-03	1268	2	3.588E-03	1308	1	2.498E-03	457	1	1.078E-02	1148	2	4.630E-03
20	2210	1	4.223E-03	484	3	3.587E-03	2981	1	2.498E-03	1049	1	9.429E-03	738	1	4.463E-03
21	1184	1	4.223E-03	473	3	3.587E-03	1626	1	2.498E-03	1050	1	9.429E-03	457	1	4.190E-03
22	1308	1	4.223E-03	2353	1	3.491E-03	1256	1	2.498E-03	2390	2	8.948E-03	984	1	3.958E-03
23	1626	1	4.223E-03	2355	2	3.491E-03	1617	1	2.498E-03	1948	1	7.954E-03	1049	1	3.871E-03
24	136	1	4.223E-03	2357	2	3.491E-03	1282	1	2.498E-03	738	1	7.873E-03	1050	1	3.871E-03
25	988	1	4.223E-03	2351	3	3.491E-03	2941	1	2.498E-03	984	1	7.423E-03	1948	1	3.727E-03
26	1893	1	4.223E-03	2349	3	3.491E-03	491	1	2.498E-03	2981	1	6.662E-03	2390	2	3.685E-03
27	1656	1	4.223E-03	1282	1	3.367E-03	1265	1	2.498E-03	1589	1	6.496E-03	2210	1	3.535E-03
28	223	1	4.223E-03	1304	2	3.367E-03	136	1	2.498E-03	1668	2	6.354E-03	1184	1	3.430E-03
29	3019	1	4.223E-03	1294	1	3.367E-03	2723	1	2.498E-03	2723	1	6.074E-03	1308	1	3.380E-03
30	1700	1	4.223E-03	1300	1	3.367E-03	2843	1	2.498E-03	2941	1	5.996E-03	2981	1	3.373E-03
31	1681	1	4.223E-03	1306	2	3.367E-03	1318	1	2.498E-03	3040	1	5.662E-03	1626	1	3.317E-03
32	3001	1	4.223E-03	1280	2	3.367E-03	1639	1	2.498E-03	1654	2	5.621E-03	1256	1	3.273E-03
33	3005	1	4.223E-03	1302	2	3.367E-03	988	1	2.498E-03	848	3	5.502E-03	1668	2	3.222E-03
34	1377	1	4.223E-03	1303	2	3.367E-03	3040	1	2.498E-03	2210	1	5.451E-03	1617	1	3.222E-03
35	874	1	4.223E-03	1290	2	3.367E-03	2842	1	2.498E-03	2563	3	5.396E-03	1282	1	3.175E-03
36	3014	1	4.223E-03	1279	3	3.367E-03	1893	1	2.498E-03	1354	2	5.315E-03	2941	1	3.165E-03
37	857	1	4.223E-03	1289	3	3.367E-03	1656	1	2.498E-03	1184	1	5.220E-03	491	1	3.164E-03
38	880	1	4.223E-03	1278	3	3.367E-03	223	1	2.498E-03	2329	2	5.220E-03	1265	1	3.157E-03
39	323	1	4.223E-03	1284	3	3.367E-03	2370	1	2.498E-03	2372	2	5.098E-03	136	1	3.124E-03
40	2282	1	4.223E-03	1846	1	3.330E-03	3019	1	2.498E-03	1282	1	4.724E-03	1654	2	3.038E-03
41	2097	1	4.223E-03	1845	2	3.330E-03	2321	1	2.498E-03	1265	1	4.429E-03	2372	2	3.012E-03
42	2996	1	4.223E-03	728	1	3.257E-03	1700	1	2.498E-03	1318	1	4.429E-03	2723	1	2.999E-03
43	3002	1	4.223E-03	738	1	3.257E-03	2745	1	2.498E-03	2321	1	4.429E-03	2843	1	2.976E-03
44	1001	1	4.223E-03	737	2	3.257E-03	1681	1	2.498E-03	1256	1	4.412E-03	1231	2	2.962E-03
45	2281	1	4.223E-03	721	1	3.257E-03	2841	1	2.498E-03	2634	1	4.236E-03	1318	1	2.941E-03
46	2503	1	4.223E-03	743	1	3.257E-03	539	1	2.498E-03	1691	3	4.188E-03	1639	1	2.939E-03
47	1717	1	4.223E-03	723	1	3.257E-03	3001	1	2.498E-03	1308	1	4.074E-03	988	1	2.931E-03
48	899	1	4.223E-03	732	1	3.257E-03	3005	1	2.498E-03	136	1	4.046E-03	3040	1	2.888E-03
49	1767	1	4.223E-03	740	3	3.257E-03	1987	1	2.498E-03	539	1	3.897E-03	2842	1	2.886E-03
50	2249	1	4.223E-03	715	1	3.257E-03	1377	1	2.498E-03	1067	1	3.865E-03	1893	1	2.825E-03
51	2641	1	4.223E-03	730	2	3.257E-03	874	1	2.498E-03	1051	2	3.536E-03	1656	1	2.800E-03
52	3000	1	4.223E-03	735	2	3.257E-03	3014	1	2.498E-03	1052	2	3.536E-03	223	1	2.791E-03
53	2956	1	4.223E-03	741	2	3.257E-03	1117	1	2.498E-03	1639	1	3.485E-03	2370	1	2.778E-03
54	2957	1	4.223E-03	733	3	3.257E-03	857	1	2.498E-03	2370	1	3.480E-03	3019	1	2.777E-03
55	1746	1	4.223E-03	704	2	3.086E-03	880	1	2.498E-03	1969	1	3.374E-03	2329	2	2.765E-03
56	2762	1	4.223E-03	710	1	3.086E-03	323	1	2.498E-03	1617	1	3.331E-03	2321	1	2.736E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
57	2652	1	4.223E-03	696	2	3.086E-03	2282	1	2.498E-03	988	1	3.317E-03	1700	1	2.728E-03
58	2014	1	4.223E-03	714	2	3.086E-03	2097	1	2.498E-03	2178	1	3.275E-03	2745	1	2.722E-03
59	3035	1	4.223E-03	698	2	3.086E-03	2996	1	2.498E-03	2282	1	3.143E-03	1681	1	2.716E-03
60	1086	1	4.223E-03	709	2	3.086E-03	3002	1	2.498E-03	2281	1	3.143E-03	2841	1	2.680E-03
61	2631	1	4.223E-03	705	2	3.086E-03	1001	1	2.498E-03	258	1	3.126E-03	539	1	2.677E-03
62	2767	1	4.223E-03	697	3	3.086E-03	2904	1	2.498E-03	557	1	3.118E-03	3001	1	2.672E-03
63	1630	2	3.167E-03	1338	1	3.053E-03	2281	1	2.498E-03	491	1	3.110E-03	3005	1	2.615E-03
64	2200	1	3.167E-03	1339	2	3.053E-03	2503	1	2.498E-03	832	2	2.983E-03	1987	1	2.590E-03
65	457	1	3.167E-03	2372	2	3.023E-03	1717	1	2.498E-03	1740	2	2.923E-03	1354	2	2.589E-03
66	1617	1	3.167E-03	2370	1	3.023E-03	899	1	2.498E-03	2997	1	2.912E-03	1377	1	2.572E-03
67	491	1	3.167E-03	2366	2	3.023E-03	2997	1	2.498E-03	704	2	2.885E-03	874	1	2.567E-03
68	1231	2	3.167E-03	2367	1	3.023E-03	2833	1	2.498E-03	2366	2	2.847E-03	3014	1	2.561E-03
69	1639	1	3.167E-03	2363	1	3.023E-03	2895	1	2.498E-03	2641	1	2.834E-03	1117	1	2.554E-03
70	2688	1	3.167E-03	1725	1	2.969E-03	1767	1	2.498E-03	2721	1	2.811E-03	857	1	2.551E-03
71	1593	2	3.167E-03	1729	2	2.969E-03	2249	1	2.498E-03	3033	1	2.761E-03	880	1	2.551E-03
72	3118	2	3.167E-03	1720	2	2.969E-03	557	1	2.498E-03	1169	1	2.761E-03	323	1	2.530E-03
73	2743	2	3.167E-03	1726	3	2.969E-03	2641	1	2.498E-03	1231	2	2.749E-03	2282	1	2.529E-03
74	303	2	3.167E-03	1724	3	2.969E-03	2688	1	2.498E-03	1123	1	2.735E-03	2097	1	2.525E-03
75	2805	2	3.167E-03	2904	1	2.941E-03	2756	1	2.498E-03	2882	2	2.673E-03	2996	1	2.514E-03
76	821	2	3.167E-03	2895	1	2.941E-03	2353	1	2.498E-03	1626	1	2.657E-03	3002	1	2.514E-03
77	2741	2	3.167E-03	2891	1	2.941E-03	2634	1	2.498E-03	1304	2	2.564E-03	1001	1	2.494E-03
78	1096	2	3.167E-03	2903	2	2.941E-03	3000	1	2.498E-03	2712	2	2.564E-03	2904	1	2.484E-03
79	2746	2	3.167E-03	2905	2	2.941E-03	1067	1	2.498E-03	2236	2	2.549E-03	2281	1	2.477E-03
80	1692	2	2.112E-03	2688	1	2.783E-03	721	1	2.498E-03	2950	1	2.501E-03	2503	1	2.466E-03
81	1254	2	2.112E-03	2692	1	2.783E-03	2956	1	2.498E-03	2219	1	2.438E-03	1304	2	2.465E-03
82	1119	2	2.112E-03	2684	3	2.783E-03	2957	1	2.498E-03	2985	1	2.413E-03	1717	1	2.457E-03
83	1110	2	2.112E-03	2687	3	2.783E-03	1746	1	2.498E-03	2714	2	2.409E-03	899	1	2.452E-03
84	1670	2	2.112E-03	2236	2	2.753E-03	1294	1	2.498E-03	2904	1	2.384E-03	2997	1	2.435E-03
85	761	2	2.112E-03	2238	2	2.753E-03	258	1	2.498E-03	2466	1	2.376E-03	2833	1	2.434E-03
86	1148	2	2.112E-03	2241	3	2.753E-03	2985	1	2.498E-03	740	3	2.338E-03	2895	1	2.425E-03
87	1049	1	2.112E-03	2243	4	2.753E-03	1887	1	2.498E-03	1767	1	2.293E-03	1767	1	2.421E-03
88	1050	1	2.112E-03	2235	4	2.753E-03	743	1	2.498E-03	2389	2	2.284E-03	2882	2	2.409E-03
89	2390	2	2.112E-03	1208	1	2.728E-03	1123	1	2.498E-03	1700	1	2.279E-03	2249	1	2.402E-03
90	2981	1	2.112E-03	1329	3	2.726E-03	2219	1	2.498E-03	737	2	2.278E-03	557	1	2.401E-03
91	1256	1	2.112E-03	1855	2	2.726E-03	723	1	2.498E-03	1893	1	2.248E-03	2641	1	2.401E-03
92	1668	2	2.112E-03	1861	2	2.726E-03	732	1	2.498E-03	1887	1	2.214E-03	2688	1	2.397E-03
93	1282	1	2.112E-03	1862	3	2.726E-03	2178	1	2.498E-03	2895	1	2.149E-03	848	3	2.394E-03
94	2941	1	2.112E-03	1308	1	2.724E-03	2692	1	2.498E-03	1107	2	2.149E-03	2756	1	2.391E-03
95	1265	1	2.112E-03	1318	1	2.724E-03	1969	1	2.498E-03	974	1	2.128E-03	2353	1	2.391E-03
96	1654	2	2.112E-03	1320	1	2.724E-03	2721	1	2.498E-03	3019	1	2.097E-03	1691	3	2.372E-03
97	2372	2	2.112E-03	1311	1	2.724E-03	2762	1	2.498E-03	1206	3	2.079E-03	737	2	2.366E-03
98	2723	1	2.112E-03	1326	2	2.724E-03	2950	1	2.498E-03	1672	3	2.033E-03	2634	1	2.360E-03
99	1318	1	2.112E-03	1323	3	2.724E-03	3033	1	2.498E-03	276	1	2.016E-03	3000	1	2.357E-03
100	3040	1	2.112E-03	1317	3	2.724E-03	2652	1	2.498E-03	768	1	2.005E-03	1067	1	2.356E-03
101	2370	1	2.112E-03	1319	2	2.724E-03	2367	1	2.498E-03	1685	3	1.990E-03	721	1	2.352E-03
102	2329	2	2.112E-03	1324	3	2.724E-03	974	1	2.498E-03	223	1	1.988E-03	2956	1	2.345E-03
103	2321	1	2.112E-03	1573	2	2.650E-03	1695	1	2.498E-03	1855	2	1.988E-03	2957	1	2.345E-03
104	539	1	2.112E-03	1562	3	2.650E-03	1846	1	2.498E-03	1058	1	1.985E-03	1746	1	2.330E-03
105	1117	1	2.112E-03	1692	2	2.604E-03	858	1	2.498E-03	2171	1	1.975E-03	1294	1	2.318E-03
106	2904	1	2.112E-03	1680	1	2.604E-03	1590	1	2.498E-03	150	2	1.957E-03	258	1	2.313E-03
107	1304	2	2.112E-03	1670	2	2.604E-03	1888	1	2.498E-03	1656	1	1.874E-03	2985	1	2.310E-03
108	2997	1	2.112E-03	1668	2	2.604E-03	2014	1	2.498E-03	899	1	1.865E-03	1887	1	2.289E-03
109	2895	1	2.112E-03	1654	2	2.604E-03	1367	1	2.498E-03	2903	2	1.854E-03	743	1	2.277E-03
110	557	1	2.112E-03	1639	1	2.604E-03	2363	1	2.498E-03	1735	2	1.842E-03	1123	1	2.266E-03
111	2353	1	2.112E-03	1656	1	2.604E-03	1725	1	2.498E-03	1741	2	1.772E-03	2219	1	2.254E-03
112	737	2	2.112E-03	1681	1	2.604E-03	1300	1	2.498E-03	3001	1	1.748E-03	2712	2	2.239E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
113	2634	1	2.112E-03	1691	3	2.604E-03	3035	1	2.498E-03	2393	1	1.745E-03	723	1	2.238E-03
114	1067	1	2.112E-03	1695	1	2.604E-03	2891	1	2.498E-03	693	1	1.744E-03	732	1	2.222E-03
115	721	1	2.112E-03	1646	1	2.604E-03	1646	1	2.498E-03	890	2	1.709E-03	2178	1	2.216E-03
116	1294	1	2.112E-03	1689	1	2.604E-03	2393	1	2.498E-03	619	1	1.691E-03	2692	1	2.212E-03
117	258	1	2.112E-03	1633	2	2.604E-03	1086	1	2.498E-03	968	2	1.686E-03	704	2	2.211E-03
118	2985	1	2.112E-03	1672	3	2.604E-03	1320	1	2.498E-03	1059	1	1.640E-03	2366	2	2.186E-03
119	1887	1	2.112E-03	1685	3	2.604E-03	2998	1	2.498E-03	2652	1	1.639E-03	1969	1	2.185E-03
120	743	1	2.112E-03	1648	2	2.604E-03	1338	1	2.498E-03	2420	3	1.594E-03	2721	1	2.183E-03
121	1123	1	2.112E-03	1686	2	2.604E-03	2631	1	2.498E-03	1117	1	1.591E-03	2762	1	2.164E-03
122	2219	1	2.112E-03	1657	2	2.604E-03	2767	1	2.498E-03	323	1	1.591E-03	2950	1	2.163E-03
123	2712	2	2.112E-03	1645	2	2.604E-03	1311	1	2.498E-03	892	1	1.580E-03	1628	2	2.163E-03
124	723	1	2.112E-03	1647	2	2.604E-03	715	1	2.498E-03	2285	2	1.569E-03	3033	1	2.162E-03
125	732	1	2.112E-03	1652	2	2.604E-03	1839	1	2.498E-03	2096	2	1.566E-03	2652	1	2.156E-03
126	2178	1	2.112E-03	1671	3	2.604E-03	768	1	2.498E-03	2743	2	1.547E-03	2367	1	2.152E-03
127	2692	1	2.112E-03	1655	3	2.604E-03	2505	1	2.498E-03	721	1	1.540E-03	974	1	2.151E-03
128	1969	1	2.112E-03	1649	3	2.604E-03	693	1	2.498E-03	1105	1	1.540E-03	1695	1	2.116E-03
129	2721	1	2.112E-03	1684	3	2.604E-03	276	1	2.498E-03	1681	1	1.538E-03	1846	1	2.115E-03
130	2950	1	2.112E-03	1687	3	2.604E-03	710	1	2.498E-03	1111	4	1.525E-03	1620	3	2.115E-03
131	1628	2	2.112E-03	1675	3	2.604E-03	1014	1	2.498E-03	2745	1	1.519E-03	2563	3	2.113E-03
132	3033	1	2.112E-03	1688	3	2.604E-03	2698	1	2.498E-03	3005	1	1.519E-03	858	1	2.113E-03
133	2367	1	2.112E-03	1666	4	2.604E-03	2517	1	2.498E-03	964	2	1.512E-03	1590	1	2.110E-03
134	974	1	2.112E-03	1660	3	2.604E-03	1715	1	2.498E-03	1100	2	1.512E-03	1888	1	2.101E-03
135	1695	1	2.112E-03	1589	1	2.513E-03	1689	1	2.498E-03	2209	2	1.499E-03	2014	1	2.099E-03
136	1846	1	2.112E-03	1590	1	2.513E-03	2386	1	2.498E-03	756	1	1.497E-03	1367	1	2.091E-03
137	1620	3	2.112E-03	1593	2	2.513E-03	1169	1	2.498E-03	858	1	1.476E-03	2363	1	2.085E-03
138	858	1	2.112E-03	1585	2	2.513E-03	2171	1	2.498E-03	2353	1	1.465E-03	1725	1	2.081E-03
139	1590	1	2.112E-03	1379	1	2.480E-03	1058	1	2.498E-03	1888	1	1.462E-03	740	3	2.073E-03
140	1888	1	2.112E-03	1377	1	2.480E-03	2087	1	2.498E-03	2576	2	1.462E-03	1300	1	2.067E-03
141	1367	1	2.112E-03	1367	1	2.480E-03	2466	1	2.498E-03	2692	1	1.454E-03	3035	1	2.066E-03
142	2363	1	2.112E-03	1369	2	2.480E-03	756	1	2.498E-03	1133	2	1.405E-03	2891	1	2.065E-03
143	1725	1	2.112E-03	1368	2	2.480E-03	619	1	2.498E-03	2530	2	1.405E-03	1605	2	2.059E-03
144	1300	1	2.112E-03	1372	3	2.480E-03	892	1	2.498E-03	2843	1	1.398E-03	1646	1	2.059E-03
145	2891	1	2.112E-03	1386	3	2.480E-03	995	1	2.498E-03	2762	1	1.398E-03	2393	1	2.054E-03
146	1605	2	2.112E-03	1375	3	2.480E-03	1553	1	2.498E-03	2951	2	1.392E-03	1086	1	2.050E-03
147	1646	1	2.112E-03	1391	3	2.480E-03	2932	1	2.498E-03	2014	1	1.363E-03	2236	2	2.044E-03
148	2393	1	2.112E-03	1384	3	2.480E-03	2376	1	2.498E-03	875	2	1.360E-03	1320	1	2.032E-03
149	1320	1	2.112E-03	1382	3	2.480E-03	2557	1	2.498E-03	1750	1	1.360E-03	2998	1	2.029E-03
150	2998	1	2.112E-03	1392	3	2.480E-03	1559	1	2.498E-03	2097	1	1.358E-03	1845	2	2.028E-03
151	1845	2	2.112E-03	2712	2	2.464E-03	1545	1	2.498E-03	1014	1	1.349E-03	2389	2	2.019E-03
152	2389	2	2.112E-03	2698	1	2.464E-03	1813	1	2.498E-03	1001	1	1.336E-03	1338	1	2.018E-03
153	1338	1	2.112E-03	2714	2	2.464E-03	869	1	2.498E-03	1738	2	1.333E-03	2631	1	2.016E-03
154	1311	1	2.112E-03	2705	2	2.464E-03	1059	1	2.498E-03	2734	1	1.322E-03	2767	1	2.012E-03
155	715	1	2.112E-03	2707	2	2.464E-03	1149	1	2.498E-03	1590	1	1.317E-03	1311	1	2.000E-03
156	1839	1	2.112E-03	2716	2	2.464E-03	2245	1	2.498E-03	1090	1	1.303E-03	715	1	1.998E-03
157	768	1	2.112E-03	2703	2	2.464E-03	948	1	2.498E-03	2505	1	1.299E-03	1839	1	1.997E-03
158	2505	1	2.112E-03	2715	3	2.464E-03	2575	1	2.498E-03	1294	1	1.295E-03	768	1	1.996E-03
159	693	1	2.112E-03	2702	3	2.464E-03	940	1	2.498E-03	2998	1	1.288E-03	2505	1	1.992E-03
160	276	1	2.112E-03	2713	3	2.464E-03	981	1	2.498E-03	1367	1	1.274E-03	693	1	1.991E-03
161	710	1	2.112E-03	223	1	2.456E-03	976	1	2.498E-03	1149	1	1.261E-03	276	1	1.988E-03
162	1014	1	2.112E-03	228	2	2.456E-03	2949	1	2.498E-03	2283	2	1.253E-03	710	1	1.985E-03
163	2698	1	2.112E-03	218	3	2.456E-03	1550	1	2.498E-03	1695	1	1.252E-03	1014	1	1.966E-03
164	2517	1	2.112E-03	874	1	2.365E-03	2256	1	2.498E-03	743	1	1.240E-03	1051	2	1.964E-03
165	1715	1	2.112E-03	857	1	2.365E-03	958	1	2.498E-03	1081	1	1.237E-03	1052	2	1.964E-03
166	1689	1	2.112E-03	880	1	2.365E-03	1131	1	2.498E-03	1839	1	1.235E-03	2698	1	1.956E-03
167	875	2	2.112E-03	858	1	2.365E-03	846	1	2.498E-03	3014	1	1.233E-03	2714	2	1.936E-03
168	2386	1	2.112E-03	875	2	2.365E-03	1750	1	2.498E-03	1717	1	1.197E-03	2517	1	1.926E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
169	1633	2	2.112E-03	869	1	2.365E-03	842	1	2.498E-03	2935	2	1.191E-03	1715	1	1.924E-03
170	1169	1	2.112E-03	873	2	2.365E-03	1140	1	2.498E-03	2392	2	1.190E-03	1689	1	1.920E-03
171	2171	1	2.112E-03	866	2	2.365E-03	2970	1	2.498E-03	874	1	1.181E-03	2903	2	1.917E-03
172	1058	1	2.112E-03	856	2	2.365E-03	1105	1	2.498E-03	1715	1	1.176E-03	497	2	1.916E-03
173	2087	1	2.112E-03	883	2	2.365E-03	690	1	2.498E-03	1620	3	1.169E-03	875	2	1.913E-03
174	2096	2	2.112E-03	884	2	2.365E-03	2734	1	2.498E-03	2082	2	1.163E-03	2386	1	1.905E-03
175	2466	1	2.112E-03	871	2	2.365E-03	909	1	2.498E-03	466	1	1.152E-03	1593	2	1.903E-03
176	968	2	2.112E-03	863	2	2.365E-03	3050	1	2.498E-03	2386	1	1.146E-03	1633	2	1.902E-03
177	756	1	2.112E-03	877	3	2.365E-03	2859	1	2.498E-03	1104	1	1.143E-03	1855	2	1.897E-03
178	1326	2	2.112E-03	881	3	2.365E-03	1090	1	2.498E-03	2688	1	1.141E-03	1169	1	1.896E-03
179	619	1	2.112E-03	862	3	2.365E-03	121	1	2.498E-03	2575	1	1.136E-03	2171	1	1.891E-03
180	892	1	2.112E-03	882	3	2.365E-03	893	1	2.498E-03	537	2	1.124E-03	1058	1	1.886E-03
181	995	1	2.112E-03	1893	1	2.332E-03	1104	1	2.498E-03	2705	2	1.124E-03	2087	1	1.884E-03
182	2209	2	2.112E-03	1887	1	2.332E-03	1081	1	2.498E-03	857	1	1.116E-03	2096	2	1.879E-03
183	1553	1	2.112E-03	1888	1	2.332E-03	466	1	2.498E-03	880	1	1.116E-03	2466	1	1.875E-03
184	1729	2	2.112E-03	3019	1	2.290E-03	2649	1	2.498E-03	2996	1	1.116E-03	968	2	1.871E-03
185	1720	2	2.112E-03	3014	1	2.290E-03	364	1	2.498E-03	3002	1	1.116E-03	756	1	1.869E-03
186	964	2	2.112E-03	3017	2	2.290E-03	1630	2	1.817E-03	2249	1	1.116E-03	1326	2	1.866E-03
187	2932	1	2.112E-03	1409	2	2.274E-03	1692	2	1.817E-03	2956	1	1.116E-03	1255	3	1.865E-03
188	2376	1	2.112E-03	1394	2	2.274E-03	2564	2	1.817E-03	2957	1	1.116E-03	619	1	1.856E-03
189	2557	1	2.112E-03	1412	3	2.274E-03	1254	2	1.817E-03	1746	1	1.116E-03	892	1	1.853E-03
190	2905	2	2.112E-03	1393	3	2.274E-03	1119	2	1.817E-03	995	1	1.114E-03	995	1	1.853E-03
191	1648	2	2.112E-03	1401	4	2.274E-03	1110	2	1.817E-03	1813	1	1.103E-03	2209	2	1.849E-03
192	1559	1	2.112E-03	2981	1	2.219E-03	1670	2	1.817E-03	1377	1	1.089E-03	1553	1	1.839E-03
193	1735	2	2.112E-03	3001	1	2.219E-03	761	2	1.817E-03	723	1	1.084E-03	1729	2	1.837E-03
194	1545	1	2.112E-03	3005	1	2.219E-03	1148	2	1.817E-03	2503	1	1.082E-03	1672	3	1.834E-03
195	1813	1	2.112E-03	2996	1	2.219E-03	2390	2	1.817E-03	1114	3	1.075E-03	1720	2	1.828E-03
196	869	1	2.112E-03	3002	1	2.219E-03	1668	2	1.817E-03	1633	2	1.075E-03	964	2	1.827E-03
197	1059	1	2.112E-03	2997	1	2.219E-03	1654	2	1.817E-03	2859	1	1.041E-03	2932	1	1.826E-03
198	1741	2	2.112E-03	3000	1	2.219E-03	2372	2	1.817E-03	2842	1	1.038E-03	2376	1	1.824E-03
199	1149	1	2.112E-03	2985	1	2.219E-03	1231	2	1.817E-03	1553	1	1.037E-03	1685	3	1.823E-03
200	2245	1	2.112E-03	2998	1	2.219E-03	2329	2	1.817E-03	2517	1	1.033E-03	2557	1	1.822E-03
201	228	2	2.112E-03	3003	2	2.219E-03	1354	2	1.817E-03	2609	3	1.032E-03	2905	2	1.822E-03
202	948	1	2.112E-03	3009	2	2.219E-03	1304	2	1.817E-03	2079	3	1.028E-03	1740	2	1.819E-03
203	2082	2	2.112E-03	2989	3	2.219E-03	2882	2	1.817E-03	732	1	1.022E-03	1648	2	1.818E-03
204	2575	1	2.112E-03	543	1	2.201E-03	737	2	1.817E-03	1646	1	1.022E-03	1559	1	1.816E-03
205	940	1	2.112E-03	539	1	2.201E-03	2712	2	1.817E-03	2649	1	9.925E-04	1735	2	1.813E-03
206	981	1	2.112E-03	537	2	2.201E-03	704	2	1.817E-03	2367	1	9.776E-04	3118	2	1.809E-03
207	976	1	2.112E-03	1354	2	2.168E-03	2366	2	1.817E-03	2977	2	9.594E-04	1545	1	1.805E-03
208	1686	2	2.112E-03	1358	2	2.168E-03	1628	2	1.817E-03	1559	1	9.448E-04	1813	1	1.801E-03
209	2949	1	2.112E-03	1341	3	2.168E-03	1605	2	1.817E-03	1535	2	9.369E-04	869	1	1.801E-03
210	832	2	2.112E-03	1365	3	2.168E-03	2236	2	1.817E-03	2932	1	9.243E-04	1059	1	1.800E-03
211	1657	2	2.112E-03	1351	3	2.168E-03	1845	2	1.817E-03	2087	1	9.064E-04	1741	2	1.795E-03
212	1550	1	2.112E-03	1363	4	2.168E-03	2389	2	1.817E-03	1545	1	9.022E-04	1149	1	1.794E-03
213	2256	1	2.112E-03	1839	1	2.143E-03	1051	2	1.817E-03	3050	1	8.874E-04	2245	1	1.792E-03
214	958	1	2.112E-03	1836	2	2.143E-03	1052	2	1.817E-03	2805	2	8.858E-04	2875	2	1.787E-03
215	1645	2	2.112E-03	1835	2	2.143E-03	2714	2	1.817E-03	959	2	8.725E-04	228	2	1.783E-03
216	1133	2	2.112E-03	1843	2	2.143E-03	2903	2	1.817E-03	189	2	8.665E-04	948	1	1.778E-03
217	873	2	2.112E-03	2503	1	2.061E-03	497	2	1.817E-03	1710	2	8.597E-04	2082	2	1.778E-03
218	1131	1	2.112E-03	2505	1	2.061E-03	875	2	1.817E-03	1763	2	8.597E-04	2575	1	1.771E-03
219	1871	2	2.112E-03	2517	1	2.061E-03	1593	2	1.817E-03	1126	2	8.597E-04	2743	2	1.767E-03
220	846	1	2.112E-03	2941	1	2.053E-03	1633	2	1.817E-03	1871	2	8.555E-04	940	1	1.755E-03
221	150	2	2.112E-03	925	2	2.032E-03	1855	2	1.817E-03	1845	2	8.522E-04	981	1	1.748E-03
222	1750	1	2.112E-03	926	3	2.032E-03	2096	2	1.817E-03	2557	1	8.491E-04	976	1	1.745E-03
223	842	1	2.112E-03	2097	1	2.020E-03	968	2	1.817E-03	1369	2	8.481E-04	1686	2	1.737E-03
224	1140	1	2.112E-03	2087	1	2.020E-03	1326	2	1.817E-03	1836	2	8.481E-04	2949	1	1.729E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
225	2970	1	2.112E-03	2096	2	2.020E-03	2209	2	1.817E-03	696	2	8.391E-04	832	2	1.728E-03
226	925	2	2.112E-03	2082	2	2.020E-03	1729	2	1.817E-03	1628	2	8.328E-04	2355	2	1.721E-03
227	1105	1	2.112E-03	2079	3	2.020E-03	1720	2	1.817E-03	2376	1	8.228E-04	1657	2	1.718E-03
228	3003	2	2.112E-03	2098	2	2.020E-03	964	2	1.817E-03	1326	2	8.119E-04	1550	1	1.715E-03
229	1192	2	2.112E-03	1028	3	2.005E-03	2905	2	1.817E-03	948	1	8.011E-04	2256	1	1.706E-03
230	690	1	2.112E-03	2200	1	1.968E-03	1740	2	1.817E-03	1320	1	7.954E-04	696	2	1.699E-03
231	2734	1	2.112E-03	2210	1	1.968E-03	1648	2	1.817E-03	1094	2	7.921E-04	958	1	1.695E-03
232	909	1	2.112E-03	2219	1	1.968E-03	1735	2	1.817E-03	2767	1	7.903E-04	1306	2	1.688E-03
233	2079	3	2.112E-03	2209	2	1.968E-03	3118	2	1.817E-03	2245	1	7.879E-04	2357	2	1.684E-03
234	3050	1	2.112E-03	2225	2	1.968E-03	1741	2	1.817E-03	1192	2	7.843E-04	1645	2	1.682E-03
235	2859	1	2.112E-03	2203	3	1.968E-03	2875	2	1.817E-03	1323	3	7.795E-04	1133	2	1.682E-03
236	866	2	2.112E-03	2207	3	1.968E-03	228	2	1.817E-03	1096	2	7.753E-04	537	2	1.681E-03
237	1090	1	2.112E-03	1001	1	1.920E-03	2082	2	1.817E-03	1817	2	7.733E-04	1280	2	1.678E-03
238	121	1	2.112E-03	1003	2	1.920E-03	2743	2	1.817E-03	1765	2	7.665E-04	1268	2	1.678E-03
239	856	2	2.112E-03	997	4	1.920E-03	1686	2	1.817E-03	2949	1	7.644E-04	873	2	1.678E-03
240	893	1	2.112E-03	2256	1	1.913E-03	832	2	1.817E-03	2631	1	7.504E-04	1131	1	1.677E-03
241	3009	2	2.112E-03	2258	3	1.913E-03	2355	2	1.817E-03	2698	1	7.495E-04	1871	2	1.669E-03
242	340	2	2.112E-03	2259	3	1.913E-03	1657	2	1.817E-03	228	2	7.457E-04	846	1	1.666E-03
243	1104	1	2.112E-03	2257	3	1.913E-03	696	2	1.817E-03	1725	1	7.438E-04	1302	2	1.662E-03
244	1024	2	2.112E-03	1700	1	1.911E-03	1306	2	1.817E-03	1776	2	7.419E-04	150	2	1.662E-03
245	955	2	2.112E-03	1717	1	1.911E-03	2357	2	1.817E-03	1648	2	7.381E-04	730	2	1.661E-03
246	1817	2	2.112E-03	1715	1	1.911E-03	1645	2	1.817E-03	2537	2	7.182E-04	1750	1	1.660E-03
247	1081	1	2.112E-03	1707	2	1.911E-03	1133	2	1.817E-03	1647	2	7.176E-04	735	2	1.655E-03
248	466	1	2.112E-03	1710	2	1.911E-03	537	2	1.817E-03	2891	1	7.095E-04	842	1	1.653E-03
249	983	2	2.112E-03	1714	2	1.911E-03	1280	2	1.817E-03	940	1	7.075E-04	1140	1	1.653E-03
250	138	2	2.112E-03	1706	3	1.911E-03	1268	2	1.817E-03	2363	1	7.073E-04	1303	2	1.650E-03
251	1707	2	2.112E-03	2329	2	1.910E-03	873	2	1.817E-03	1131	1	7.024E-04	1206	3	1.638E-03
252	980	2	2.112E-03	2325	3	1.910E-03	1871	2	1.817E-03	981	1	6.947E-04	2970	1	1.638E-03
253	2649	1	2.112E-03	1014	1	1.907E-03	1302	2	1.817E-03	1255	3	6.929E-04	303	2	1.637E-03
254	2285	2	2.112E-03	1024	2	1.907E-03	150	2	1.817E-03	121	1	6.817E-04	925	2	1.630E-03
255	364	1	2.112E-03	1023	2	1.907E-03	730	2	1.817E-03	846	1	6.778E-04	1105	1	1.630E-03
256	3036	2	2.112E-03	1010	2	1.907E-03	735	2	1.817E-03	1317	3	6.681E-04	714	2	1.626E-03
257	1763	2	2.112E-03	1022	3	1.907E-03	1303	2	1.817E-03	1311	1	6.643E-04	3003	2	1.624E-03
258	1765	2	2.112E-03	2321	1	1.906E-03	303	2	1.817E-03	2248	2	6.291E-04	1861	2	1.623E-03
259	2420	3	2.112E-03	189	2	1.903E-03	925	2	1.817E-03	842	1	6.276E-04	1192	2	1.623E-03
260	2609	3	2.112E-03	214	3	1.903E-03	714	2	1.817E-03	275	2	6.264E-04	690	1	1.622E-03
261	2613	2	2.112E-03	205	3	1.903E-03	3003	2	1.817E-03	909	1	6.186E-04	741	2	1.622E-03
262	2768	2	2.112E-03	1871	2	1.893E-03	1861	2	1.817E-03	1140	1	6.077E-04	2734	1	1.617E-03
263	1094	2	2.112E-03	557	1	1.877E-03	1192	2	1.817E-03	2569	2	6.077E-04	2705	2	1.615E-03
264	1776	2	2.112E-03	974	1	1.868E-03	741	2	1.817E-03	2057	2	5.869E-04	909	1	1.613E-03
265	2640	2	2.112E-03	968	2	1.868E-03	2705	2	1.817E-03	2001	2	5.800E-04	2079	3	1.612E-03
266	2009	2	2.112E-03	964	2	1.868E-03	866	2	1.817E-03	2640	2	5.765E-04	3050	1	1.612E-03
267	2607	3	2.112E-03	976	1	1.868E-03	698	2	1.817E-03	1775	2	5.668E-04	2859	1	1.609E-03
268	2761	3	2.112E-03	958	1	1.868E-03	1290	2	1.817E-03	925	2	5.607E-04	866	2	1.603E-03
269	2752	3	2.112E-03	955	2	1.868E-03	709	2	1.817E-03	1835	2	5.550E-04	698	2	1.600E-03
270	2643	2	2.112E-03	959	2	1.868E-03	856	2	1.817E-03	714	2	5.453E-04	1290	2	1.599E-03
271	497	2	1.584E-03	979	2	1.868E-03	2805	2	1.817E-03	1550	1	5.413E-04	709	2	1.598E-03
272	537	2	1.584E-03	978	3	1.868E-03	821	2	1.817E-03	465	2	5.386E-04	1090	1	1.598E-03
273	1861	2	1.584E-03	977	3	1.868E-03	3009	2	1.817E-03	2355	2	5.217E-04	121	1	1.597E-03
274	2098	2	1.584E-03	956	3	1.868E-03	340	2	1.817E-03	1846	1	5.214E-04	856	2	1.597E-03
275	2001	2	1.584E-03	960	4	1.868E-03	705	2	1.817E-03	1652	2	5.170E-04	2805	2	1.588E-03
276	2057	2	1.584E-03	2390	2	1.862E-03	1024	2	1.817E-03	730	2	5.128E-04	821	2	1.582E-03
277	2004	2	1.584E-03	2393	1	1.862E-03	955	2	1.817E-03	1306	2	5.107E-04	1279	3	1.578E-03
278	848	3	1.408E-03	2389	2	1.862E-03	1369	2	1.817E-03	340	2	5.051E-04	893	1	1.573E-03
279	1691	3	1.408E-03	2386	1	1.862E-03	1647	2	1.817E-03	976	1	5.035E-04	3009	2	1.565E-03
280	740	3	1.408E-03	2376	1	1.862E-03	1817	2	1.817E-03	218	3	5.029E-04	2886	3	1.563E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
281	1255	3	1.408E-03	2392	2	1.862E-03	1339	2	1.817E-03	1562	3	5.002E-04	340	2	1.561E-03
282	1672	3	1.408E-03	2397	2	1.862E-03	1652	2	1.817E-03	308	2	4.951E-04	1104	1	1.557E-03
283	1685	3	1.408E-03	2378	2	1.862E-03	2741	2	1.817E-03	735	2	4.915E-04	705	2	1.556E-03
284	1206	3	1.408E-03	2384	2	1.862E-03	1096	2	1.817E-03	2768	2	4.915E-04	1024	2	1.554E-03
285	1279	3	1.408E-03	2377	3	1.862E-03	1319	2	1.817E-03	3000	1	4.900E-04	955	2	1.554E-03
286	1323	3	1.408E-03	3118	2	1.843E-03	983	2	1.817E-03	205	3	4.889E-04	1369	2	1.550E-03
287	1317	3	1.408E-03	2557	1	1.830E-03	2392	2	1.817E-03	901	3	4.838E-04	1323	3	1.550E-03
288	1329	3	1.408E-03	2544	2	1.830E-03	138	2	1.817E-03	1280	2	4.745E-04	1647	2	1.549E-03
289	1671	3	1.408E-03	2546	3	1.830E-03	2746	2	1.817E-03	1760	2	4.707E-04	1817	2	1.548E-03
290	1655	3	1.408E-03	323	1	1.809E-03	1707	2	1.817E-03	2741	2	4.684E-04	1339	2	1.539E-03
291	1649	3	1.408E-03	340	2	1.809E-03	980	2	1.817E-03	1689	1	4.642E-04	1081	1	1.533E-03
292	1684	3	1.408E-03	1184	1	1.778E-03	1836	2	1.817E-03	3017	2	4.615E-04	1317	3	1.522E-03
293	1687	3	1.408E-03	1206	3	1.778E-03	1573	2	1.817E-03	893	1	4.583E-04	466	1	1.520E-03
294	1675	3	1.408E-03	1192	2	1.778E-03	2935	2	1.817E-03	1729	2	4.511E-04	1652	2	1.498E-03
295	1688	3	1.408E-03	2932	1	1.771E-03	1585	2	1.817E-03	3038	2	4.511E-04	2741	2	1.497E-03
296	877	3	1.408E-03	2935	2	1.771E-03	2951	2	1.817E-03	942	2	4.445E-04	1096	2	1.495E-03
297	881	3	1.408E-03	2923	3	1.771E-03	890	2	1.817E-03	698	2	4.429E-04	1319	2	1.489E-03
298	926	3	1.408E-03	2920	3	1.771E-03	2530	2	1.817E-03	1585	2	4.385E-04	983	2	1.488E-03
299	214	3	1.408E-03	2249	1	1.770E-03	2238	2	1.817E-03	1862	3	4.385E-04	2392	2	1.481E-03
300	1028	3	1.408E-03	2245	1	1.770E-03	2285	2	1.817E-03	709	2	4.330E-04	138	2	1.481E-03
301	2258	3	1.408E-03	2248	2	1.770E-03	2098	2	1.817E-03	827	3	4.330E-04	2746	2	1.473E-03
302	978	3	1.408E-03	2252	2	1.770E-03	1738	2	1.817E-03	303	2	4.315E-04	1707	2	1.473E-03
303	1706	3	1.408E-03	2255	2	1.770E-03	2576	2	1.817E-03	1289	3	4.252E-04	980	2	1.468E-03
304	936	3	1.408E-03	2254	3	1.770E-03	2707	2	1.817E-03	363	2	4.240E-04	2649	1	1.466E-03
305	901	3	1.408E-03	2253	3	1.770E-03	1368	2	1.817E-03	3036	2	4.228E-04	1836	2	1.466E-03
306	1114	3	1.408E-03	2250	3	1.770E-03	1710	2	1.817E-03	1135	2	4.196E-04	1573	2	1.463E-03
307	1730	3	1.408E-03	2244	3	1.770E-03	189	2	1.817E-03	1605	2	4.184E-04	1329	3	1.460E-03
308	827	3	1.408E-03	2246	3	1.770E-03	883	2	1.817E-03	2905	2	4.184E-04	2935	2	1.459E-03
309	891	3	1.408E-03	2251	3	1.770E-03	3036	2	1.817E-03	873	2	4.184E-04	1585	2	1.456E-03
310	911	3	1.408E-03	136	1	1.727E-03	3017	2	1.817E-03	955	2	4.184E-04	2951	2	1.452E-03
311	918	3	1.408E-03	138	2	1.727E-03	959	2	1.817E-03	1329	3	4.176E-04	890	2	1.451E-03
312	1115	3	1.408E-03	1123	1	1.719E-03	2716	2	1.817E-03	1720	2	4.152E-04	2530	2	1.450E-03
313	2642	3	1.408E-03	1126	2	1.719E-03	2703	2	1.817E-03	1686	2	4.152E-04	2238	2	1.447E-03
314	1091	3	1.408E-03	1121	4	1.719E-03	884	2	1.817E-03	2613	2	4.117E-04	1289	3	1.446E-03
315	1777	3	1.408E-03	1553	1	1.710E-03	1835	2	1.817E-03	3118	2	4.096E-04	2285	2	1.437E-03
316	1778	3	1.408E-03	1559	1	1.710E-03	1535	2	1.817E-03	1338	1	4.088E-04	484	3	1.427E-03
317	1092	3	1.408E-03	1545	1	1.710E-03	1409	2	1.817E-03	1302	2	4.079E-04	2098	2	1.426E-03
318	2564	2	1.056E-03	1550	1	1.710E-03	1394	2	1.817E-03	979	2	4.060E-04	364	1	1.422E-03
319	1354	2	1.056E-03	1535	2	1.710E-03	871	2	1.817E-03	2203	3	4.049E-04	1738	2	1.422E-03
320	2882	2	1.056E-03	1552	2	1.710E-03	1763	2	1.817E-03	2970	1	4.018E-04	2576	2	1.418E-03
321	704	2	1.056E-03	1560	2	1.710E-03	1126	2	1.817E-03	883	2	3.970E-04	2707	2	1.416E-03
322	2366	2	1.056E-03	948	1	1.701E-03	863	2	1.817E-03	497	2	3.833E-04	473	3	1.411E-03
323	2236	2	1.056E-03	940	1	1.701E-03	1107	2	1.817E-03	2397	2	3.831E-04	1368	2	1.411E-03
324	1051	2	1.056E-03	942	2	1.701E-03	2977	2	1.817E-03	1024	2	3.821E-04	1710	2	1.411E-03
325	1052	2	1.056E-03	949	2	1.701E-03	1765	2	1.817E-03	692	2	3.808E-04	189	2	1.411E-03
326	2714	2	1.056E-03	936	3	1.701E-03	1843	2	1.817E-03	2357	2	3.731E-04	2351	3	1.409E-03
327	2903	2	1.056E-03	935	3	1.701E-03	1358	2	1.817E-03	2746	2	3.728E-04	1671	3	1.409E-03
328	1855	2	1.056E-03	984	1	1.688E-03	2248	2	1.817E-03	1086	1	3.698E-04	883	2	1.409E-03
329	1740	2	1.056E-03	988	1	1.688E-03	2001	2	1.817E-03	1861	2	3.666E-04	3036	2	1.408E-03
330	2875	2	1.056E-03	995	1	1.688E-03	979	2	1.817E-03	1303	2	3.607E-04	3017	2	1.406E-03
331	2355	2	1.056E-03	981	1	1.688E-03	2397	2	1.817E-03	741	2	3.600E-04	959	2	1.403E-03
332	696	2	1.056E-03	983	2	1.688E-03	2537	2	1.817E-03	949	2	3.585E-04	2716	2	1.402E-03
333	1306	2	1.056E-03	980	2	1.688E-03	2613	2	1.817E-03	1319	2	3.582E-04	2703	2	1.398E-03
334	2357	2	1.056E-03	993	3	1.688E-03	1714	2	1.817E-03	1726	3	3.579E-04	884	2	1.394E-03
335	1280	2	1.056E-03	2843	1	1.672E-03	2378	2	1.817E-03	3003	2	3.510E-04	1835	2	1.393E-03
336	1268	2	1.056E-03	2842	1	1.672E-03	2057	2	1.817E-03	1751	3	3.447E-04	2349	3	1.388E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria: Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
337	1302	2	1.056E-03	2841	1	1.672E-03	942	2	1.817E-03	821	2	3.447E-04	1655	3	1.385E-03
338	730	2	1.056E-03	693	1	1.612E-03	1023	2	1.817E-03	1987	1	3.423E-04	1649	3	1.383E-03
339	735	2	1.056E-03	690	1	1.612E-03	1010	2	1.817E-03	689	2	3.419E-04	1684	3	1.380E-03
340	1303	2	1.056E-03	692	2	1.612E-03	2768	2	1.817E-03	1657	2	3.407E-04	1535	2	1.380E-03
341	714	2	1.056E-03	689	2	1.612E-03	2384	2	1.817E-03	884	2	3.368E-04	1278	3	1.378E-03
342	741	2	1.056E-03	683	3	1.612E-03	1094	2	1.817E-03	983	2	3.360E-04	1862	3	1.377E-03
343	2705	2	1.056E-03	2956	1	1.542E-03	949	2	1.817E-03	1409	2	3.343E-04	1687	3	1.373E-03
344	698	2	1.056E-03	2957	1	1.542E-03	2225	2	1.817E-03	1671	3	3.341E-04	1409	2	1.370E-03
345	1290	2	1.056E-03	2950	1	1.542E-03	1552	2	1.817E-03	1573	2	3.282E-04	1394	2	1.367E-03
346	709	2	1.056E-03	2949	1	1.542E-03	1003	2	1.817E-03	1755	2	3.272E-04	871	2	1.365E-03
347	705	2	1.056E-03	2970	1	1.542E-03	692	2	1.817E-03	2655	2	3.267E-04	1763	2	1.364E-03
348	1369	2	1.056E-03	2951	2	1.542E-03	1776	2	1.817E-03	2707	2	3.266E-04	1284	3	1.364E-03
349	1647	2	1.056E-03	2977	2	1.542E-03	2544	2	1.817E-03	1394	2	3.227E-04	1675	3	1.363E-03
350	1339	2	1.056E-03	2530	2	1.522E-03	689	2	1.817E-03	953	2	3.206E-04	1126	2	1.363E-03
351	1652	2	1.056E-03	2537	2	1.522E-03	275	2	1.817E-03	2989	3	3.111E-04	863	2	1.359E-03
352	1319	2	1.056E-03	258	1	1.516E-03	1560	2	1.817E-03	1552	2	3.096E-04	1688	3	1.355E-03
353	2392	2	1.056E-03	249	3	1.516E-03	2569	2	1.817E-03	2715	3	3.037E-04	733	3	1.351E-03
354	1836	2	1.056E-03	782	3	1.491E-03	2252	2	1.817E-03	958	1	3.021E-04	1107	2	1.348E-03
355	1573	2	1.056E-03	1813	1	1.491E-03	2255	2	1.817E-03	2256	1	2.998E-04	2977	2	1.343E-03
356	2935	2	1.056E-03	1817	2	1.491E-03	1135	2	1.817E-03	2684	3	2.998E-04	1765	2	1.341E-03
357	1585	2	1.056E-03	1790	3	1.491E-03	1100	2	1.817E-03	1843	2	2.951E-04	1726	3	1.330E-03
358	2951	2	1.056E-03	1746	1	1.482E-03	3038	2	1.817E-03	2009	2	2.934E-04	1843	2	1.328E-03
359	890	2	1.056E-03	1740	2	1.482E-03	2640	2	1.817E-03	1300	1	2.928E-04	2420	3	1.327E-03
360	2530	2	1.056E-03	1735	2	1.482E-03	1732	2	1.817E-03	1368	2	2.915E-04	1358	2	1.326E-03
361	2238	2	1.056E-03	1741	2	1.482E-03	2009	2	1.817E-03	2378	2	2.900E-04	2248	2	1.318E-03
362	1738	2	1.056E-03	1738	2	1.482E-03	308	2	1.817E-03	2565	2	2.866E-04	877	3	1.299E-03
363	2576	2	1.056E-03	1732	2	1.482E-03	2565	2	1.817E-03	2761	3	2.860E-04	697	3	1.299E-03
364	2707	2	1.056E-03	1730	3	1.482E-03	2722	2	1.817E-03	1944	2	2.847E-04	2609	3	1.295E-03
365	1368	2	1.056E-03	1747	3	1.482E-03	2283	2	1.817E-03	2098	2	2.838E-04	881	3	1.293E-03
366	1710	2	1.056E-03	1049	1	1.447E-03	2717	2	1.817E-03	2716	2	2.708E-04	2001	2	1.291E-03
367	189	2	1.056E-03	1050	1	1.447E-03	767	2	1.817E-03	138	2	2.687E-04	979	2	1.287E-03
368	883	2	1.056E-03	1051	2	1.447E-03	851	2	1.817E-03	690	1	2.684E-04	1562	3	1.286E-03
369	3017	2	1.056E-03	1052	2	1.447E-03	917	2	1.817E-03	705	2	2.667E-04	2397	2	1.280E-03
370	959	2	1.056E-03	2193	3	1.401E-03	363	2	1.817E-03	2752	3	2.657E-04	2537	2	1.278E-03
371	2716	2	1.056E-03	1133	2	1.394E-03	2643	2	1.817E-03	1358	2	2.648E-04	2613	2	1.272E-03
372	2703	2	1.056E-03	1131	1	1.394E-03	1760	2	1.817E-03	3035	1	2.645E-04	1724	3	1.272E-03
373	884	2	1.056E-03	1140	1	1.394E-03	1755	2	1.817E-03	1747	3	2.579E-04	2684	3	1.269E-03
374	1835	2	1.056E-03	1135	2	1.394E-03	2004	2	1.817E-03	980	2	2.567E-04	1714	2	1.257E-03
375	1535	2	1.056E-03	1142	4	1.394E-03	465	2	1.817E-03	2642	3	2.553E-04	2378	2	1.256E-03
376	1862	3	1.056E-03	850	1	1.376E-03	1754	2	1.817E-03	2703	2	2.546E-04	2057	2	1.255E-03
377	1409	2	1.056E-03	848	3	1.376E-03	1775	2	1.817E-03	1268	2	2.523E-04	942	2	1.255E-03
378	1394	2	1.056E-03	846	1	1.376E-03	953	2	1.817E-03	2259	3	2.468E-04	1023	2	1.254E-03
379	871	2	1.056E-03	842	1	1.376E-03	1944	2	1.817E-03	2193	3	2.468E-04	1010	2	1.244E-03
380	1126	2	1.056E-03	851	2	1.376E-03	835	2	1.817E-03	1279	3	2.461E-04	2768	2	1.239E-03
381	863	2	1.056E-03	761	2	1.369E-03	2655	2	1.817E-03	1714	2	2.451E-04	218	3	1.238E-03
382	1107	2	1.056E-03	768	1	1.369E-03	1243	2	1.817E-03	710	1	2.435E-04	2384	2	1.236E-03
383	2977	2	1.056E-03	756	1	1.369E-03	848	3	1.289E-03	2833	1	2.422E-04	1094	2	1.235E-03
384	1843	2	1.056E-03	767	2	1.369E-03	1691	3	1.289E-03	1560	2	2.401E-04	949	2	1.233E-03
385	1358	2	1.056E-03	751	3	1.369E-03	1620	3	1.289E-03	214	3	2.386E-04	2241	3	1.231E-03
386	2248	2	1.056E-03	2575	1	1.339E-03	2563	3	1.289E-03	1023	2	2.383E-04	2225	2	1.229E-03
387	979	2	1.056E-03	2576	2	1.339E-03	740	3	1.289E-03	2254	3	2.372E-04	926	3	1.225E-03
388	2397	2	1.056E-03	2569	2	1.339E-03	1255	3	1.289E-03	1655	3	2.370E-04	2687	3	1.225E-03
389	2537	2	1.056E-03	2565	2	1.339E-03	1672	3	1.289E-03	1649	3	2.327E-04	1552	2	1.223E-03
390	1714	2	1.056E-03	2568	3	1.339E-03	1685	3	1.289E-03	1339	2	2.293E-04	1003	2	1.217E-03
391	2378	2	1.056E-03	276	1	1.327E-03	1206	3	1.289E-03	869	1	2.271E-04	692	2	1.216E-03
392	942	2	1.056E-03	275	2	1.327E-03	2079	3	1.289E-03	1341	3	2.250E-04	1776	2	1.212E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
393	1023	2	1.056E-03	2723	1	1.314E-03	1279	3	1.289E-03	871	2	2.216E-04	214	3	1.210E-03
394	1010	2	1.056E-03	2721	1	1.314E-03	2886	3	1.289E-03	1684	3	2.192E-04	2544	2	1.208E-03
395	2384	2	1.056E-03	2722	2	1.314E-03	1323	3	1.289E-03	2841	1	2.171E-04	1028	3	1.207E-03
396	949	2	1.056E-03	2717	2	1.314E-03	1317	3	1.289E-03	2722	2	2.103E-04	1324	3	1.207E-03
397	2225	2	1.056E-03	2718	3	1.314E-03	1329	3	1.289E-03	2384	2	2.082E-04	689	2	1.207E-03
398	1552	2	1.056E-03	1148	2	1.307E-03	1289	3	1.289E-03	823	3	2.079E-04	275	2	1.206E-03
399	1003	2	1.056E-03	1149	1	1.307E-03	484	3	1.289E-03	364	1	2.052E-04	1560	2	1.206E-03
400	692	2	1.056E-03	1152	3	1.307E-03	473	3	1.289E-03	977	3	2.016E-04	2569	2	1.205E-03
401	2544	2	1.056E-03	3040	1	1.279E-03	2351	3	1.289E-03	863	2	1.980E-04	2715	3	1.190E-03
402	689	2	1.056E-03	3033	1	1.279E-03	1671	3	1.289E-03	2756	1	1.975E-04	1666	4	1.190E-03
403	275	2	1.056E-03	3035	1	1.279E-03	2349	3	1.289E-03	1010	2	1.970E-04	2258	3	1.186E-03
404	1560	2	1.056E-03	3036	2	1.279E-03	1655	3	1.289E-03	1243	2	1.968E-04	2252	2	1.186E-03
405	2569	2	1.056E-03	3038	2	1.279E-03	1649	3	1.289E-03	1645	2	1.960E-04	2255	2	1.185E-03
406	1666	4	1.056E-03	899	1	1.223E-03	1684	3	1.289E-03	1732	2	1.954E-04	1660	3	1.183E-03
407	2252	2	1.056E-03	892	1	1.223E-03	1278	3	1.289E-03	1687	3	1.918E-04	1135	2	1.172E-03
408	2255	2	1.056E-03	909	1	1.223E-03	1862	3	1.289E-03	2875	2	1.869E-04	978	3	1.165E-03
409	1135	2	1.056E-03	893	1	1.223E-03	1687	3	1.289E-03	1790	3	1.851E-04	1372	3	1.156E-03
410	1100	2	1.056E-03	890	2	1.223E-03	1284	3	1.289E-03	1121	4	1.813E-04	1706	3	1.154E-03
411	3038	2	1.056E-03	901	3	1.223E-03	1675	3	1.289E-03	2607	3	1.808E-04	1386	3	1.152E-03
412	1732	2	1.056E-03	917	2	1.223E-03	1688	3	1.289E-03	1022	3	1.782E-04	1100	2	1.151E-03
413	308	2	1.056E-03	891	3	1.223E-03	733	3	1.289E-03	2241	3	1.775E-04	3038	2	1.151E-03
414	2565	2	1.056E-03	911	3	1.223E-03	1726	3	1.289E-03	2717	2	1.743E-04	2702	3	1.149E-03
415	2722	2	1.056E-03	918	3	1.223E-03	2420	3	1.289E-03	751	3	1.732E-04	1375	3	1.149E-03
416	2283	2	1.056E-03	887	3	1.223E-03	877	3	1.289E-03	926	3	1.719E-04	1391	3	1.144E-03
417	2717	2	1.056E-03	905	3	1.223E-03	697	3	1.289E-03	2886	3	1.706E-04	1384	3	1.139E-03
418	767	2	1.056E-03	895	4	1.223E-03	2609	3	1.289E-03	2253	3	1.650E-04	1382	3	1.139E-03
419	851	2	1.056E-03	1987	1	1.185E-03	881	3	1.289E-03	2238	2	1.621E-04	2640	2	1.138E-03
420	917	2	1.056E-03	2001	2	1.185E-03	1562	3	1.289E-03	1290	2	1.581E-04	1732	2	1.137E-03
421	1111	4	1.056E-03	303	2	1.133E-03	1724	3	1.289E-03	733	3	1.554E-04	2009	2	1.133E-03
422	363	2	1.056E-03	308	2	1.133E-03	2684	3	1.289E-03	2250	3	1.546E-04	936	3	1.133E-03
423	997	4	1.056E-03	619	1	1.124E-03	218	3	1.289E-03	2351	3	1.542E-04	2989	3	1.131E-03
424	1760	2	1.056E-03	1086	1	1.108E-03	2241	3	1.289E-03	2244	3	1.531E-04	1392	3	1.126E-03
425	2193	3	1.056E-03	121	1	1.098E-03	926	3	1.289E-03	2207	3	1.528E-04	308	2	1.125E-03
426	1755	2	1.056E-03	2564	2	1.062E-03	2687	3	1.289E-03	1372	3	1.521E-04	2565	2	1.125E-03
427	465	2	1.056E-03	2563	3	1.062E-03	214	3	1.289E-03	1278	3	1.518E-04	2713	3	1.123E-03
428	1754	2	1.056E-03	2559	3	1.062E-03	1028	3	1.289E-03	891	3	1.517E-04	2243	4	1.115E-03
429	1775	2	1.056E-03	2057	2	1.034E-03	1324	3	1.289E-03	1675	3	1.506E-04	862	3	1.111E-03
430	953	2	1.056E-03	821	2	9.990E-04	2715	3	1.289E-03	2257	3	1.481E-04	882	3	1.104E-03
431	823	3	1.056E-03	827	3	9.990E-04	2258	3	1.289E-03	2643	2	1.462E-04	901	3	1.101E-03
432	1142	4	1.056E-03	823	3	9.990E-04	1660	3	1.289E-03	683	3	1.462E-04	2722	2	1.099E-03
433	1944	2	1.056E-03	2178	1	9.807E-04	978	3	1.289E-03	2718	3	1.462E-04	2235	4	1.097E-03
434	835	2	1.056E-03	2171	1	9.807E-04	1372	3	1.289E-03	2004	2	1.446E-04	1341	3	1.096E-03
435	2655	2	1.056E-03	3050	1	9.504E-04	1706	3	1.289E-03	1754	2	1.426E-04	205	3	1.096E-03
436	1243	2	1.056E-03	3044	3	9.504E-04	1386	3	1.289E-03	2702	3	1.402E-04	2283	2	1.094E-03
437	818	3	1.056E-03	1067	1	9.494E-04	2702	3	1.289E-03	917	2	1.381E-04	2203	3	1.092E-03
438	2563	3	7.039E-04	1058	1	9.494E-04	1375	3	1.289E-03	1660	3	1.358E-04	2717	2	1.090E-03
439	2886	3	7.039E-04	1059	1	9.494E-04	1391	3	1.289E-03	877	3	1.339E-04	1412	3	1.090E-03
440	1289	3	7.039E-04	364	1	8.721E-04	1384	3	1.289E-03	2258	3	1.339E-04	1114	3	1.085E-03
441	484	3	7.039E-04	363	2	8.721E-04	1382	3	1.289E-03	936	3	1.339E-04	2607	3	1.083E-03
442	473	3	7.039E-04	2859	1	7.864E-04	936	3	1.289E-03	1386	3	1.336E-04	767	2	1.081E-03
443	2351	3	7.039E-04	150	2	7.605E-04	2989	3	1.289E-03	911	3	1.332E-04	1393	3	1.075E-03
444	2349	3	7.039E-04	1973	1	7.551E-04	1392	3	1.289E-03	249	3	1.317E-04	851	2	1.069E-03
445	1278	3	7.039E-04	1969	1	7.551E-04	2713	3	1.289E-03	2544	2	1.310E-04	1365	3	1.067E-03
446	1284	3	7.039E-04	2609	3	7.489E-04	862	3	1.289E-03	2377	3	1.285E-04	917	2	1.058E-03
447	733	3	7.039E-04	2613	2	7.489E-04	882	3	1.289E-03	1028	3	1.275E-04	1730	3	1.058E-03
448	1726	3	7.039E-04	2607	3	7.489E-04	901	3	1.289E-03	484	3	1.269E-04	2761	3	1.056E-03

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
449	697	3	7.039E-04	1756	1	6.691E-04	1341	3	1.289E-03	1101	3	1.264E-04	1351	3	1.055E-03
450	1562	3	7.039E-04	1767	1	6.691E-04	205	3	1.289E-03	715	1	1.250E-04	1111	4	1.054E-03
451	1724	3	7.039E-04	1750	1	6.691E-04	2203	3	1.289E-03	2687	3	1.247E-04	2752	3	1.051E-03
452	2684	3	7.039E-04	1763	2	6.691E-04	1412	3	1.289E-03	1724	3	1.241E-04	363	2	1.042E-03
453	218	3	7.039E-04	1765	2	6.691E-04	1114	3	1.289E-03	818	3	1.222E-04	2259	3	1.038E-03
454	2241	3	7.039E-04	1760	2	6.691E-04	2607	3	1.289E-03	1375	3	1.215E-04	827	3	1.032E-03
455	2687	3	7.039E-04	1755	2	6.691E-04	1393	3	1.289E-03	956	3	1.210E-04	2643	2	1.030E-03
456	1324	3	7.039E-04	1754	2	6.691E-04	1365	3	1.289E-03	1688	3	1.207E-04	2207	3	1.029E-03
457	2715	3	7.039E-04	1751	3	6.691E-04	1730	3	1.289E-03	782	3	1.199E-04	997	4	1.020E-03
458	1660	3	7.039E-04	1753	4	6.691E-04	2761	3	1.289E-03	993	3	1.181E-04	1022	3	1.020E-03
459	1372	3	7.039E-04	2833	1	6.623E-04	1351	3	1.289E-03	866	2	1.174E-04	891	3	1.018E-03
460	1386	3	7.039E-04	2634	1	5.931E-04	2752	3	1.289E-03	2559	3	1.173E-04	977	3	1.016E-03
461	2702	3	7.039E-04	2631	1	5.931E-04	2259	3	1.289E-03	697	3	1.155E-04	2257	3	1.014E-03
462	1375	3	7.039E-04	1110	2	5.675E-04	827	3	1.289E-03	2243	4	1.146E-04	911	3	1.013E-03
463	1391	3	7.039E-04	1114	3	5.675E-04	2207	3	1.289E-03	1593	2	1.135E-04	1760	2	1.003E-03
464	1384	3	7.039E-04	1111	4	5.675E-04	1022	3	1.289E-03	3009	2	1.124E-04	2254	3	1.000E-03
465	1382	3	7.039E-04	1115	3	5.675E-04	891	3	1.289E-03	1324	3	1.119E-04	2325	3	9.985E-04
466	2989	3	7.039E-04	1109	3	5.675E-04	977	3	1.289E-03	1115	3	1.104E-04	2193	3	9.983E-04
467	1392	3	7.039E-04	2745	1	5.355E-04	2257	3	1.289E-03	1109	3	1.090E-04	2377	3	9.960E-04
468	2713	3	7.039E-04	2756	1	5.355E-04	911	3	1.289E-03	881	3	1.079E-04	956	3	9.955E-04
469	862	3	7.039E-04	2762	1	5.355E-04	2254	3	1.289E-03	935	3	1.078E-04	1401	4	9.848E-04
470	882	3	7.039E-04	2767	1	5.355E-04	2325	3	1.289E-03	1365	3	1.070E-04	2253	3	9.820E-04
471	1341	3	7.039E-04	2743	2	5.355E-04	2193	3	1.289E-03	1391	3	1.029E-04	918	3	9.814E-04
472	205	3	7.039E-04	2734	1	5.355E-04	2377	3	1.289E-03	2546	3	1.006E-04	2546	3	9.810E-04
473	2203	3	7.039E-04	2741	2	5.355E-04	956	3	1.289E-03	2246	3	1.004E-04	2250	3	9.794E-04
474	1412	3	7.039E-04	2746	2	5.355E-04	2253	3	1.289E-03	2251	3	9.986E-05	2244	3	9.790E-04
475	1393	3	7.039E-04	2768	2	5.355E-04	918	3	1.289E-03	2252	2	9.983E-05	1755	2	9.672E-04
476	1365	3	7.039E-04	2761	3	5.355E-04	2546	3	1.289E-03	887	3	9.881E-05	2246	3	9.659E-04
477	1351	3	7.039E-04	2752	3	5.355E-04	2250	3	1.289E-03	2255	2	9.793E-05	2251	3	9.657E-04
478	2259	3	7.039E-04	2466	1	5.131E-04	2244	3	1.289E-03	1284	3	9.544E-05	2004	2	9.641E-04
479	2207	3	7.039E-04	2805	2	4.833E-04	2246	3	1.289E-03	856	2	9.544E-05	2923	3	9.624E-04
480	1022	3	7.039E-04	1104	1	4.773E-04	2251	3	1.289E-03	1106	3	9.429E-05	2920	3	9.506E-04
481	977	3	7.039E-04	1090	1	4.769E-04	2923	3	1.289E-03	978	3	9.326E-05	935	3	9.505E-04
482	2257	3	7.039E-04	835	2	4.578E-04	2920	3	1.289E-03	1412	3	9.323E-05	993	3	9.497E-04
483	2254	3	7.039E-04	953	2	4.130E-04	935	3	1.289E-03	2568	3	9.289E-05	1363	4	9.488E-04
484	2325	3	7.039E-04	1105	1	3.682E-04	993	3	1.289E-03	2325	3	9.064E-05	683	3	9.378E-04
485	2377	3	7.039E-04	1107	2	3.682E-04	683	3	1.289E-03	2284	3	8.908E-05	1747	3	9.332E-04
486	956	3	7.039E-04	1106	3	3.682E-04	1747	3	1.289E-03	2923	3	8.560E-05	465	2	9.323E-04
487	2253	3	7.039E-04	457	1	3.181E-04	1790	3	1.289E-03	862	3	8.442E-05	1754	2	9.211E-04
488	2546	3	7.039E-04	466	1	3.181E-04	249	3	1.289E-03	1384	3	8.205E-05	1790	3	9.173E-04
489	2250	3	7.039E-04	465	2	3.181E-04	782	3	1.289E-03	1382	3	8.098E-05	249	3	9.103E-04
490	2244	3	7.039E-04	2420	3	3.147E-04	823	3	1.289E-03	767	2	8.059E-05	1775	2	9.046E-04
491	2246	3	7.039E-04	2014	1	3.112E-04	751	3	1.289E-03	1003	2	7.639E-05	953	2	9.015E-04
492	2251	3	7.039E-04	2009	2	3.112E-04	2718	3	1.289E-03	3044	3	7.564E-05	782	3	9.011E-04
493	2923	3	7.039E-04	2004	2	3.112E-04	2568	3	1.289E-03	2225	2	7.457E-05	823	3	8.880E-04
494	2920	3	7.039E-04	1081	1	2.831E-04	1115	3	1.289E-03	1777	3	7.273E-05	751	3	8.839E-04
495	935	3	7.039E-04	2652	1	2.630E-04	1152	3	1.289E-03	1401	4	7.166E-05	1142	4	8.808E-04
496	993	3	7.039E-04	2649	1	2.630E-04	887	3	1.289E-03	1152	3	6.970E-05	960	4	8.746E-04
497	683	3	7.039E-04	2282	1	2.524E-04	905	3	1.289E-03	2349	3	6.888E-05	1121	4	8.736E-04
498	1747	3	7.039E-04	2285	2	2.524E-04	2559	3	1.289E-03	1778	3	6.876E-05	2718	3	8.632E-04
499	1790	3	7.039E-04	2283	2	2.524E-04	3044	3	1.289E-03	473	3	6.408E-05	2568	3	8.563E-04
500	249	3	7.039E-04	2284	3	2.524E-04	1751	3	1.289E-03	1351	3	5.768E-05	1944	2	8.477E-04
501	782	3	7.039E-04	2289	4	2.524E-04	2642	3	1.289E-03	882	3	5.694E-05	1115	3	8.437E-04
502	751	3	7.039E-04	1948	1	2.335E-04	1091	3	1.289E-03	1730	3	5.199E-05	1152	3	8.424E-04
503	2718	3	7.039E-04	1944	2	2.335E-04	1777	3	1.289E-03	1707	2	5.197E-05	835	2	8.395E-04
504	2568	3	7.039E-04	1096	2	2.209E-04	1778	3	1.289E-03	895	4	4.555E-05	887	3	8.287E-04

Table 5.1 Prioritized repair order at Newport-Inglewood Mw7.1 scenario earthquake corresponding to criteria (continued).

Repair order	Criteria														
	Difficulty			Importance			Urgency			Cost			Mix		
	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value	Bridge ID	Damage state	Priority value
505	1152	3	7.039E-04	1094	2	2.209E-04	1092	3	1.289E-03	2235	4	4.176E-05	2655	2	8.094E-04
506	887	3	7.039E-04	1100	2	2.209E-04	1109	3	1.289E-03	1753	4	3.954E-05	905	3	8.076E-04
507	905	3	7.039E-04	1091	3	2.209E-04	818	3	1.289E-03	2920	3	3.821E-05	1243	2	8.073E-04
508	2559	3	7.039E-04	1092	3	2.209E-04	1106	3	1.289E-03	997	4	3.718E-05	2559	3	7.931E-04
509	3044	3	7.039E-04	1101	3	2.209E-04	1101	3	1.289E-03	960	4	3.677E-05	3044	3	7.548E-04
510	1751	3	7.039E-04	1169	1	2.122E-04	2284	3	1.289E-03	2713	3	3.674E-05	1751	3	7.517E-04
511	1109	3	7.039E-04	1776	2	1.789E-04	1666	4	1.066E-03	1091	3	3.532E-05	2642	3	7.498E-04
512	1106	3	7.039E-04	1775	2	1.789E-04	2243	4	1.066E-03	1363	4	3.392E-05	1091	3	7.383E-04
513	1101	3	7.039E-04	1777	3	1.789E-04	2235	4	1.066E-03	1666	4	3.347E-05	1777	3	7.372E-04
514	2284	3	7.039E-04	1778	3	1.789E-04	1111	4	1.066E-03	1393	3	3.228E-05	1778	3	7.362E-04
515	2243	4	5.279E-04	1243	2	1.597E-04	997	4	1.066E-03	1392	3	2.983E-05	1092	3	7.351E-04
516	2235	4	5.279E-04	1246	4	1.597E-04	1401	4	1.066E-03	2289	4	2.788E-05	895	4	7.155E-04
517	1401	4	5.279E-04	2641	1	4.700E-05	1363	4	1.066E-03	835	2	2.761E-05	1109	3	6.674E-04
518	1363	4	5.279E-04	2640	2	4.700E-05	1142	4	1.066E-03	851	2	2.760E-05	818	3	6.168E-04
519	960	4	5.279E-04	2643	2	4.700E-05	960	4	1.066E-03	1092	3	2.239E-05	1106	3	6.139E-04
520	1121	4	5.279E-04	2642	3	4.700E-05	1121	4	1.066E-03	905	3	1.459E-05	1101	3	5.851E-04
521	895	4	5.279E-04	2281	1	4.533E-05	895	4	1.066E-03	1246	4	1.458E-05	2284	3	5.837E-04
522	1753	4	5.279E-04	2655	2	3.852E-05	1753	4	1.066E-03	1142	4	7.416E-06	1753	4	5.756E-04
523	2289	4	5.279E-04	832	2	5.378E-07	2289	4	1.066E-03	1706	3	6.793E-06	2289	4	4.685E-04
524	1246	4	5.279E-04	818	3	8.228E-13	1246	4	1.066E-03	918	3	6.003E-06	1246	4	4.420E-04

5.4 Bridge restoration curves

As physical recovery of highway network from seismic damage, the bridge restoration curves simulated on 6 repair orders are obtained and illustrated in Figure 5.10. These curves are estimated on Markov Chain process model, the constrained repair condition algorithm and repair prioritization procedure. And, these results are the mean value of 400 times of Monte Carlo simulation. Depending on each repair order prioritized by each criterion, bridge restoration curve changes significantly each other. The completion date of bridge reconstruction work according to repair priority is that the day of simultaneous repair is Day 147, the day of cost priority is Day 161, the day of urgency priority is Day 168, the day of mix priority is Day 168, the day of difficulty priority is Day 175 and the day of importance priority is Day 175. And, the recovery speeds of each repair order during whole restoration period are almost same as this order. The difference of completion date between the earliest day and the latest day is about one month, and the gap between cost priority (i.e., fastest completion except for simultaneous repair)

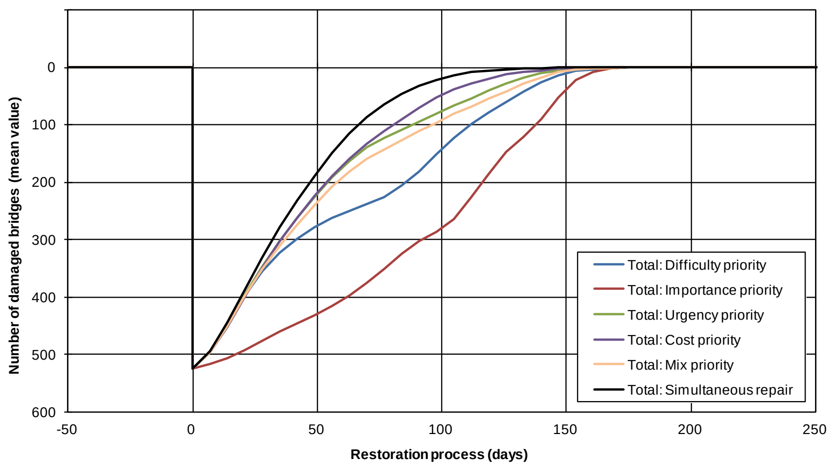


Figure 5.10 Bridge restoration curves of 6 repair orders.

and importance priority is still about two weeks. The earliest scenario other than simultaneous repair is achieved by cost priority, and the bridges with cheaper repair cost are given more priority to start reconstruction work in this criterion. The slowest bridge recovery progress over the entire period is the process simulated on importance priority. On Day 100, for example, the number of repaired bridges in importance priority is 236 (i.e., about 45% of all damaged bridges), whereas that in other repair orders is from 373 to 502 (i.e., from 71% to 96%). Especially, at the beginning of restoration process, the degree of bridge recovery of importance priority is much lower than that of other orders. Therefore, the repair order based on importance criterion is not the most effective choice for the physical recovery of highway network.

5.5 Social loss restoration curves

The social loss restoration curves corresponding to repair orders are depicted for representing performance recovery of highway network in Figure 5.11, and it is divided in the drivers' delay restoration curves and the opportunity loss restoration curves as shown in Figure 5.12 and Figure 5.13, respectively. The restoration curve consisted of performance loss (i.e. drivers' delay and opportunity loss) and recovery time is an appropriate tool for observing network's reaction to an earthquake in terms of resilience and robustness (Bruneau et al., 2003 and Chang & Shinozuka, 2004). These curves are the results of highway traffic analysis performed on the updating bridge damage status (i.e., physical damage of highway network) simulated in the previous section and the traffic demand recovering assumed in section 2.5 at every certain time until the network restitutes to the pre-earthquake condition. At each time, drivers' delay and opportunity loss of highway network is calculated corresponding to all repair scenarios, and the sum of them is defined as social loss in this study. In obvious, restoration process of highway traffic performance changes drastically depending on bridge repair order and this difference is more apparent than that of simulations for Northridge earthquake shown in Figure 4.36. This is because more damaged bridges due to Newport-Inglewood scenario earthquake strongly effect on the reconstruction progress. The recovery progress which starts all damaged bridges' repair simultaneously drawn with black line achieves the fastest completion in all three kinds of restoration curve. In respect of social loss, the full recovery date comes in the order of cost, urgency, mix, difficulty and importance as well as bridge recovery. Except the case of simultaneous repair, the recovery process on cost priority is the fastest during entire reconstruction period, and this coincides with the bridge recovery process. Therefore, in this case, this order to repair more bridges as quickly as possible is the best way for highway performance because this repair order seems to make more damaged routes reopen faster and establish more alternative highway routes for detouring. The repair progresses of other four scenarios are back and forth according to time. Indeed, the lowest level of recovery is the process of urgency priority on Day 50, meanwhile the process of difficulty priority is progressing at the slowest pace on Day 100 and the progress of urgency priority accomplishes the earlier level next to that of cost priority. If the highway performance level is focused on, about 60 days

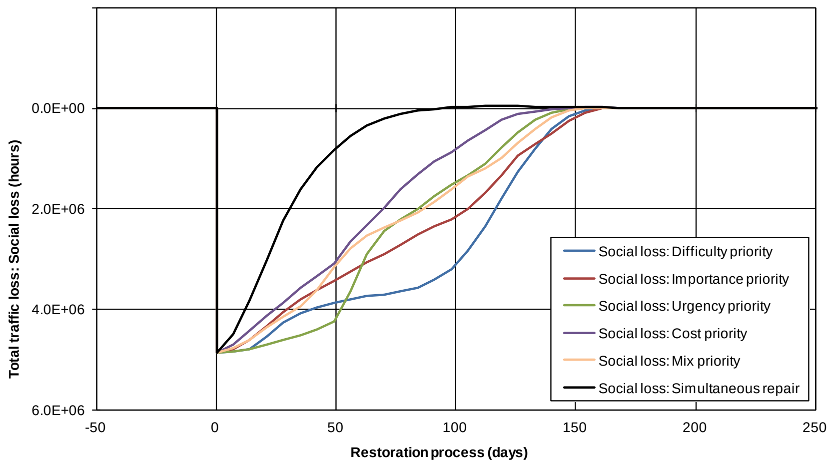


Figure 5.11 Social loss restoration curves of 6 repair orders.

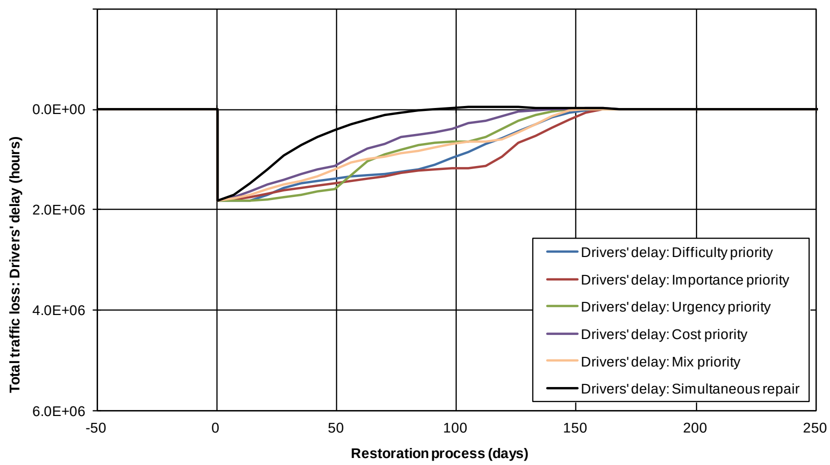


Figure 5.12 Drivers' delay restoration curves of 6 repair orders.

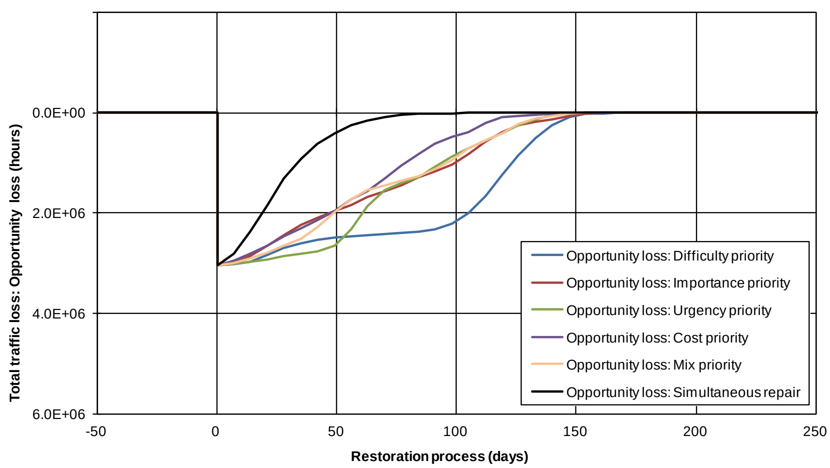


Figure 5.13 Opportunity loss restoration curves of 6 repair orders.

is needed to recover 50% in cost priority but it takes about 110 days to achieve half recovery in difficulty priority (about 1.8 times longer time). Therefore, social loss restoration process is significantly affected by reconstruction order such as decision-making of repair prioritization. When the social loss restoration curves are compared with the bridge restoration curves shown in Figure 5.10, the social loss restoration of importance priority is not the worst progress though the damaged bridge recovery of importance priority is much slower than that of other priorities. In fact, the recovery speed of important priority during the beginning term is almost same rate as that of cost priority which is the fastest process. This means that traffic performance loss is effectively restored by repairing more important bridges first which locate on links with heavier traffic volume. On the other hand, in this sense, the difficulty priority negatively affects the efficient restoration in terms of traffic performance. As to restoration curves of drivers' delay and opportunity loss, the progress trend of both restoration curves are almost same as corresponding social loss restoration curves except for importance priority. The recovery of drivers' delay on importance priority is not fast as compared to other priorities, but its recovery of opportunity loss is much quicker relatively. This means that the trip numbers are recovered quickly because travel demand is stimulated effectively by importance repair prioritization. On the other hand, the drivers' delay recovery on importance priority during the latter half is the slowest because the delay of bridge repair has an adverse influence on total driving time. In addition, travel demand on difficulty priority is not promoted very much over entire restoration period, and this negative result effects on the worse recovery of social loss of difficulty priority.

The performance restoration curves relating to business loss are illustrated in Figure 5.14 to Figure 5.16, and the recoveries of highway performance about non-business loss are expressed in Figure 5.17 to Figure 5.19. As defined in section 2.8, the business loss caused by traffic

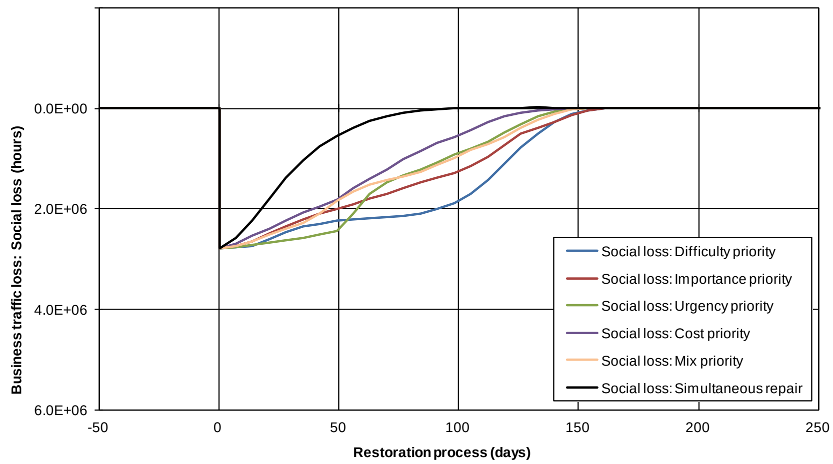


Figure 5.14 Social loss restoration curves of 6 repair orders (business relating).

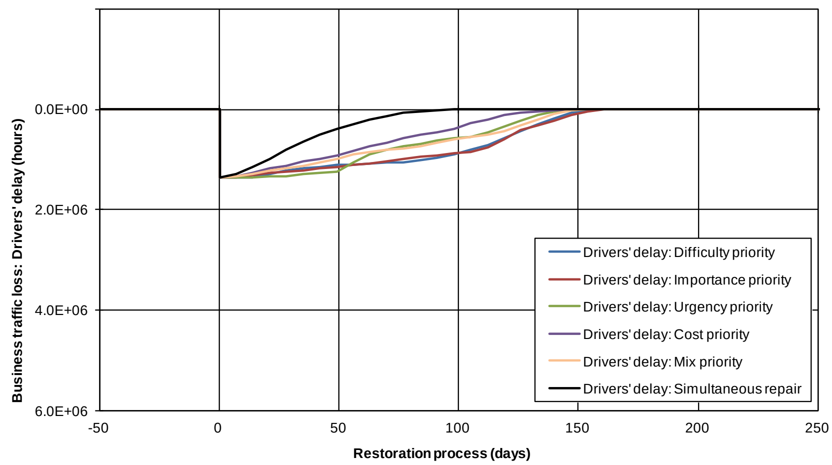


Figure 5.15 Drivers' delay restoration curves of 6 repair orders (business relating).

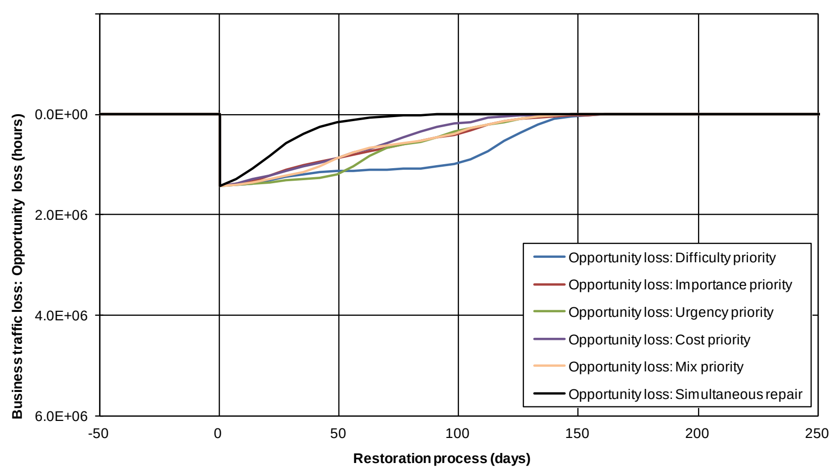


Figure 5.16 Opportunity loss restoration curves of 6 repair orders (business relating).

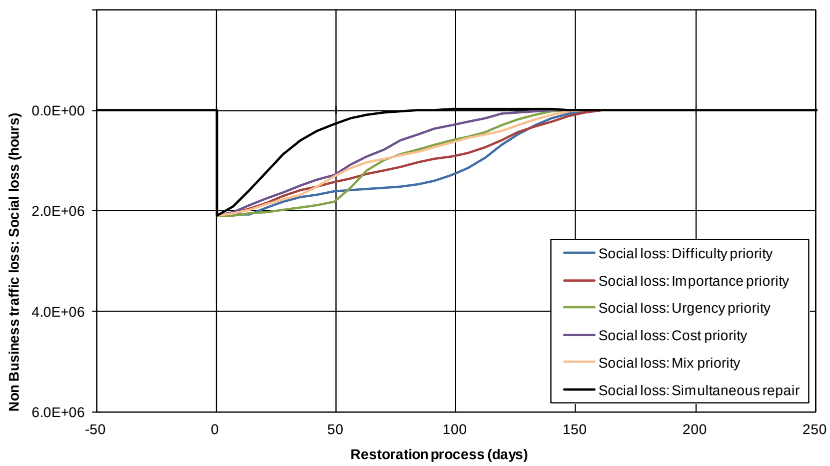


Figure 5.17 Social loss restoration curves of 6 repair orders (non-business relating).

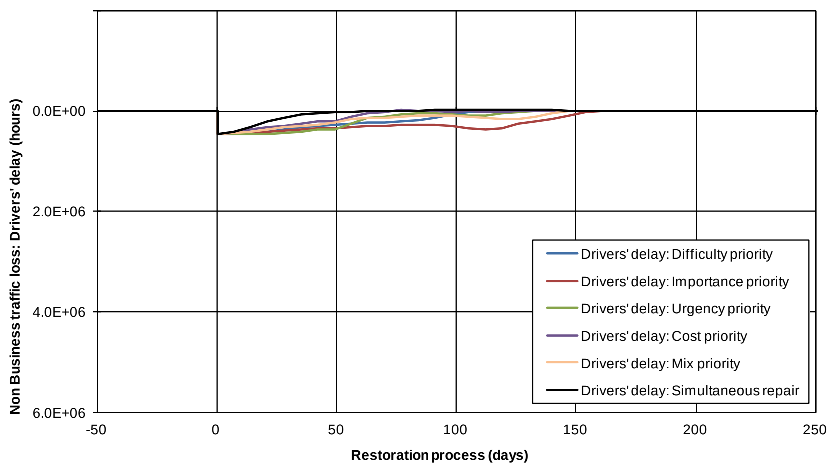


Figure 5.18 Drivers' delay restoration curves of 6 repair orders (non-business relating).

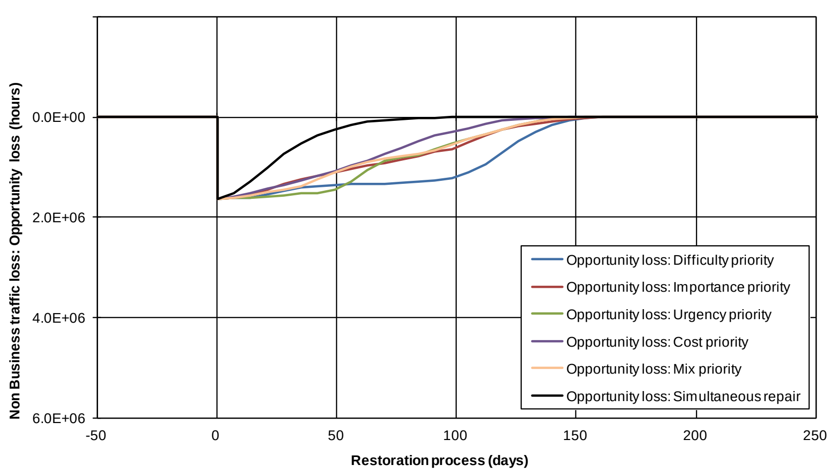


Figure 5.19 Opportunity loss restoration curves of 6 repair orders (non-business relating).

impairment consists of three trip types such as home-work, other-work and truck trip, and the non-business loss is induced by the degraded trip efficiency of home-other, other-other and home-shop trips. When the initial degradation of traffic performance of business trips is compared with that of non-business trips, the initial social loss of business trips is about 25% more than that of non-business trips. And, the initial drivers' delay time relating to business trips is about 3 times as much as non-business trips' one. On the other hand, the initial opportunity loss of business trips is about 13% less than that of non-business trips. From these comparisons, the seismic impact to business trips' efficiency is more serious than the performance loss of non-business trips. The total driving time of business trips is significantly increased by seismic damage of highway network. This is because the severe damage around the center of broader Los Angeles area caused by Newport-Inglewood scenario earthquake seems to effect on many routes relating to heavy business trips. The number of canceled trips of non-business trips (i.e., trip opportunity loss) is much more than that of business trips. Therefore, the motivation of vehicle trips for non-business tasks is thought not to be provided very much under seismic damaged society. The traffic demand for business trips seems not to be decreased very much by seismic damage, so it is conceivable that the many business trips are executed even under the inconvenient road situation due to earthquake. The daily progresses of restoration processes of both business loss and non-business loss corresponding to repair orders show same tendency as total restoration curves as indicated in Figure 5.11 to Figure 5.13. This tendency is also found in all restoration curves of social loss, drivers' delay and opportunity loss. Therefore, the difference of highway performance loss during the entire restoration period between each prioritized repair order can be considered to be same for both business loss and non-business loss.

This means that the repair order prioritized by cost criterion is the most effective in the case of Newport-Inglewood scenario earthquake as examined in the previous part.

5.6 Economic loss

An integration value of restoration curve from Day 0 to the completion date represents total performance loss due to the earthquake during an entire restoration process, and this accumulated loss calls resilience in general. This total performance loss is converted from time loss to economic loss, and it is compared with other results in monetary value after adding total bridge repair cost as shown in Figure 5.20. The first bar chart shows the total social losses in time domain based on 6 restoration processes corresponding to repair prioritizations, and the second diagram indicates the monetary values of 6 different total social losses which are

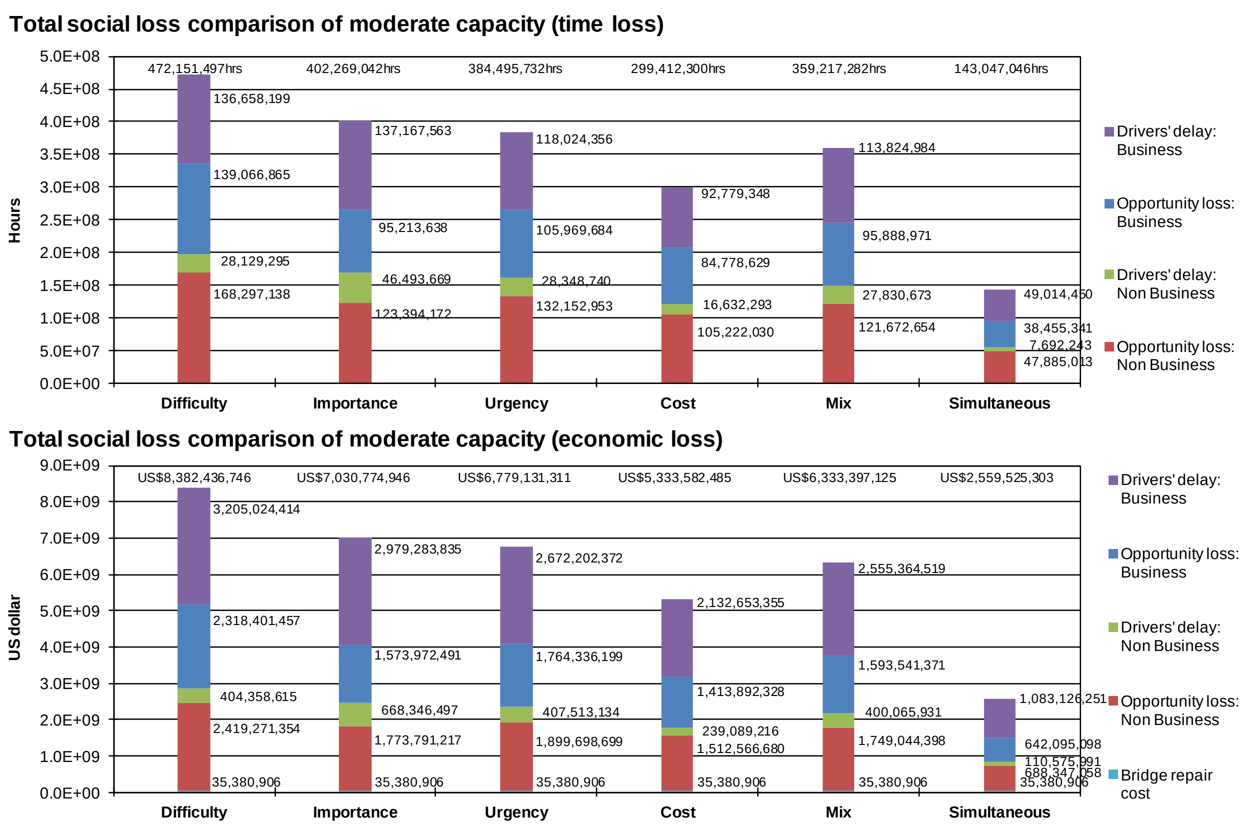


Figure 5.20 Monetary value and total time of social loss of 6 repair orders.

converted from the social time loss and are added to the total bridge repair cost. The conversion from drivers' time to monetary value (2012 U.S. dollars) is done based on Caltrans estimation described in section 2.8, and the total bridge repair cost is estimated by multiplying the replacement cost per unit area specified in section 2.8 by bridge deck area and bridge damage ratio. The total social loss in both charts is subdivided into several categories such as drivers' delay, opportunity loss, business relating loss and non-business relating loss.

The smallest economic loss next to the simultaneous repair, US$ 2,559,525,303, is the loss of cost priority. And, the economic loss increases in the following order; cost priority, mix priority, urgency priority, importance priority and difficulty priority. The total loss amount of cost priority is US$ 5,333,582,485 including bridge repair cost. The largest economic loss during entire restoration period is induced by the difficulty priority, and it is US$ 8,382,436,746. As compared with these loss amounts, the total cost of bridge reconstruction, US$ 35,380,906, is not a large portion of the total economic loss. The difference of amount between cost priority and difficulty priority is about 3 billion dollars, and the loss of difficulty priority is about 1.6 times as much as that of cost priority. The difference between simultaneous repair and difficulty priority is about 5.8 billion dollars and 3.3 times just for reference. Although the initial damage states of highway network are obviously identical for all restoration scenarios, the total economic losses accumulating performance loss until full-recovery vary enormously depending on repair orders (i.e., decision making at the early period). The rate of business loss to the total economic loss is about 65%, and this rate does not change very much depending on each repair priority. And, business loss is about 1.8 times as much as non-business loss. Therefore, the trip types relating to business are impacted much more than non-business trips in the case of Newport-Inglewood scenario earthquake. As a result, the total economic loss is strongly affected by repair order under post-earthquake recovery process, and the loss caused by highway performance degradation is much more serious than bridge repair cost. Also, the economic loss relating to business traffic activities is more significant than the non-business loss.

5.7 Sensitivity analysis

The residual traffic capacity considering seismic route damage and local route capacity are proposed in section 2.5 by following the previous researches. These capacity reduction rates are basically assumptive values in this study because there is not any specific information about this phenomenon under post-earthquake situation. In this study, three levels of decreased capacity rates, low, moderate and high, as shown in Table 2.2 are adopted, and the moderate level is considered to be the most appropriate rate by the verification study with an existing estimation of Northridge earthquake in section 4.3.2. However, a comparison investigation of residual traffic capacity is conducted here because traffic analysis result is highly sensitive to the traffic capacity. Three kinds of residual traffic capacity are therefore applied to the entire simulation based on the same analysis conditions stated in section 5.1.

From an examination of sensitivity study, both total drivers' delay and opportunity loss increase as the residual traffic capacity comes down, and the increasing rate of loss from high to low or moderate to low is almost same for all repair orders. The increasing rate of drivers' delay from high to low is about 6 times and the rate from moderate to low is about 3 times. The increasing rate of opportunity loss from high to low is about 14 times and the rate from moderate to low is about 3 times. Here, opportunity loss under high residual traffic capacity is quite small compared to other two capacity levels' cases. In fact, the amount of total opportunity loss is less than that of total derivers' delay in high traffic capacity case though total opportunity loss is about 1.6 times as large as drivers' delay in other two cases. This means that the number of canceled trips and travel time loss (i.e., opportunity loss) is decreased drastically if alternative routes/lanes could be prepared sufficiently and the residual traffic capacity would be kept high level. On the other hand, if those detours could not be established effectively after an earthquake, total social loss as the sum of drivers' delay and opportunity loss increases considerably. All results of sensitivity analysis are shown separately according to repair order as follows.

As to a sensitivity study under the repair order prioritized by difficulty criterion, restoration curves of three capacity levels are illustrated in Figure 5.21 to Figure 5.23 and rearranged graphs for comparing difference between capacity levels are depicted in Figure 5.24 to Figure 5.26. The total social loss is calculated in economic value and time length as shown in Figure 5.27. And, the comparisons of total seismic losses and relative rates between different capacity rates are listed in Table 5.2.

As to a sensitivity study under the repair order prioritized by importance criterion, restoration curves of three capacity levels are illustrated in Figure 5.28 to Figure 5.30 and rearranged graphs for comparing difference between capacity levels are depicted in Figure 5.31 to Figure 5.33. The total social loss is calculated in economic value and time length as shown in Figure 5.34. And, the comparisons of total seismic losses and relative rates between different capacity rates are listed in Table 5.3.

As to a sensitivity study under the repair order prioritized by urgency criterion, restoration curves of three capacity levels are illustrated in Figure 5.35 to Figure 5.37 and rearranged graphs for comparing difference between capacity levels are depicted in Figure 5.38 to Figure 5.40. The total social loss is calculated in economic value and time length as shown in Figure 5.41. And, the comparisons of total seismic losses and relative rates between different capacity rates are listed in Table 5.4.

As to a sensitivity study under the repair order prioritized by cost criterion, restoration curves of three capacity levels are illustrated in Figure 5.42 to Figure 5.44 and rearranged graphs for comparing difference between capacity levels are depicted in Figure 5.45 to Figure 5.47. The total social loss is calculated in economic value and time length as shown in Figure 5.48. And, the comparisons of total seismic losses and relative rates between different capacity rates are listed in Table 5.5.

As to a sensitivity study under the repair order prioritized by mixed criteria, restoration curves of three capacity levels are illustrated in Figure 5.49 to Figure 5.51 and rearranged graphs for comparing difference between capacity levels are depicted in Figure 5.52 to Figure 5.54. The total social loss is calculated in economic value and time length as shown in Figure 5.55. And, the comparisons of total seismic losses and relative rates between different capacity rates are listed in Table 5.6.

As to a sensitivity study under the simultaneous repair, restoration curves of three capacity levels are illustrated in Figure 5.56 to Figure 5.58 and rearranged graphs for comparing difference between capacity levels are depicted in Figure 5.59 to Figure 5.61. The total social loss is calculated in economic value and time length as shown in Figure 5.62. And, the comparisons of total seismic losses and relative rates between different capacity rates are listed in Table 5.7.

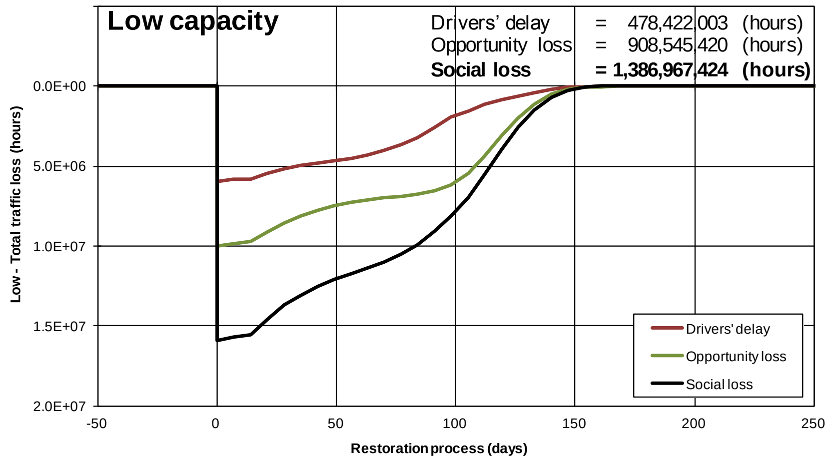


Figure 5.21 Social loss restoration curve: Low capacity & Difficulty.

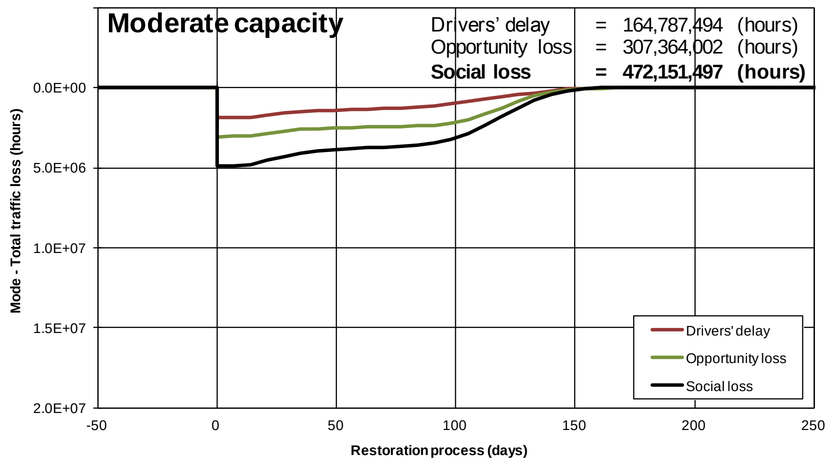


Figure 5.22 Social loss restoration curve: Moderate capacity & Difficulty.

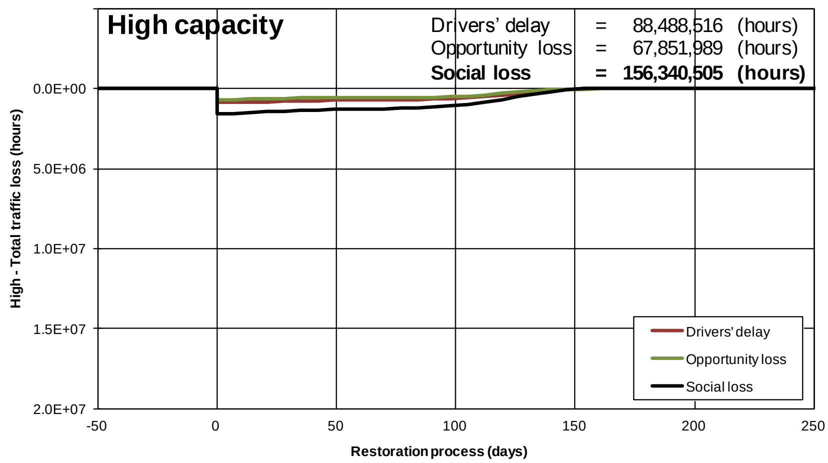


Figure 5.23 Social loss restoration curve: High capacity & Difficulty.

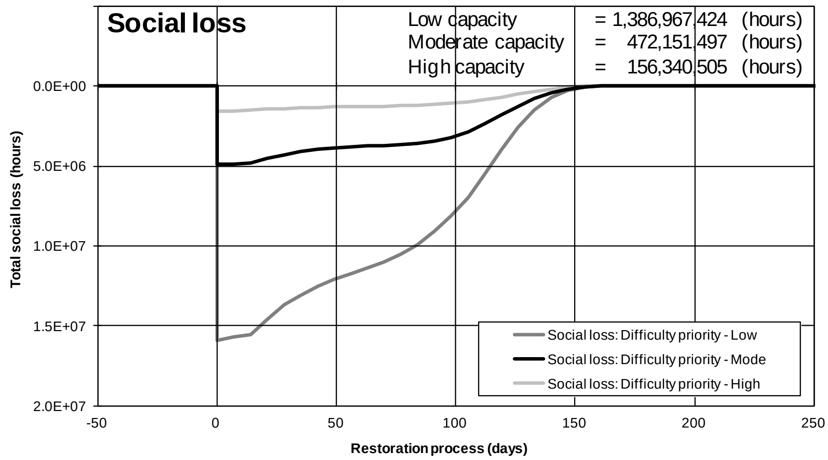


Figure 5.24 Social loss restoration curve: comparison of 3 capacities & Difficulty.

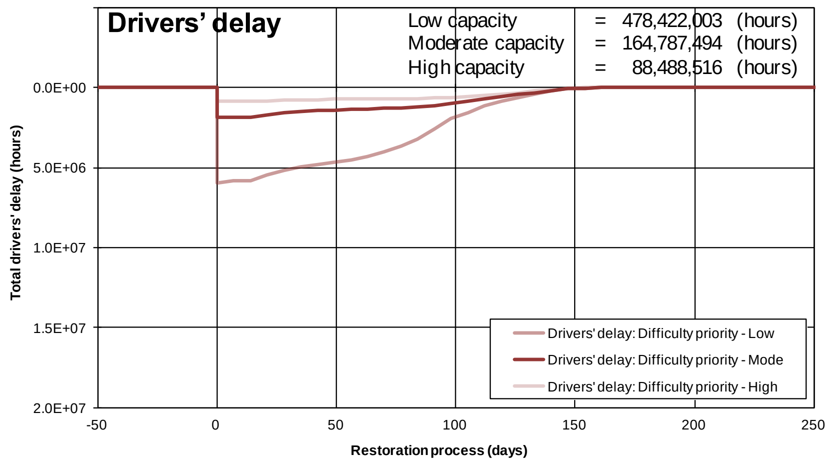


Figure 5.25 Drivers' delay restoration curve: comparison of 3 capacities & Difficulty.

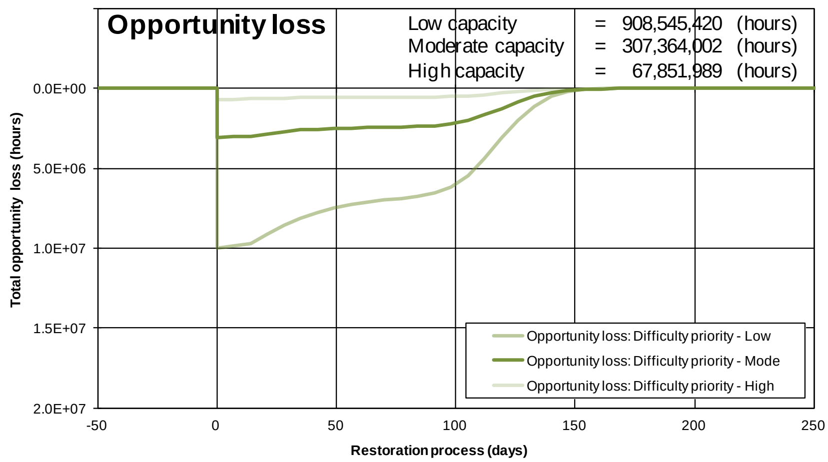
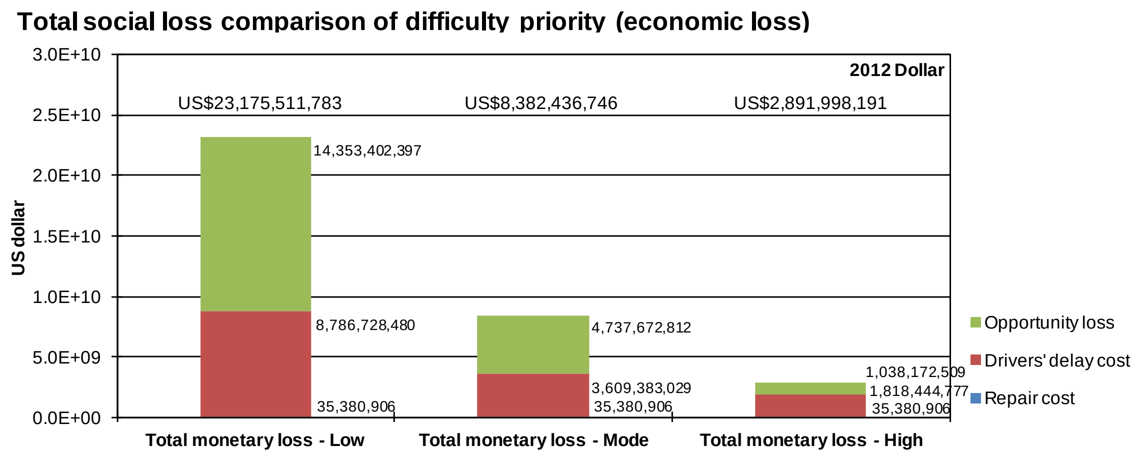


Figure 5.26 Opportunity loss restoration curve: comparison of 3 capacities & Difficulty.

Table 5.2 Total seismic loss (hours): comparison of 3 capacities & Difficulty.

Seicmic loss (hours)	Residual traffic capacity level					
	Low		Moderate		High	
Total drivers' delay	478,422,003	(1.00) (0.34)	164,787,494	(0.34) (0.35)	88,488,516	(0.18) (0.57)
Total opportunity loss	908,545,420	(1.00) (0.66)	307,364,002	(0.34) (0.65)	67,851,989	(0.07) (0.43)
Total social loss	1,386,967,424	(1.00) (1.00)	472,151,497	(0.34) (1.00)	156,340,505	(0.11) (1.00)



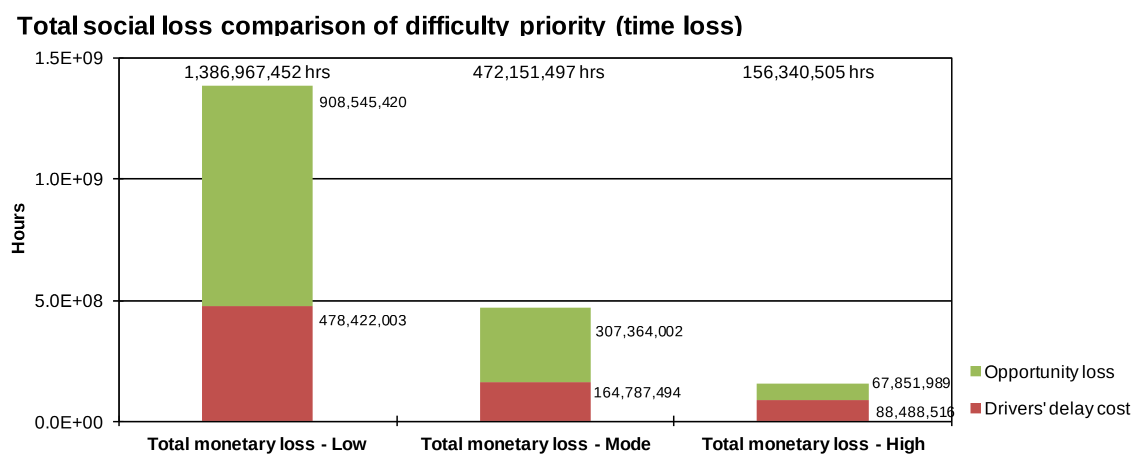


Figure 5.27 Monetary value and total time of social loss of 3 capacities & Difficulty.

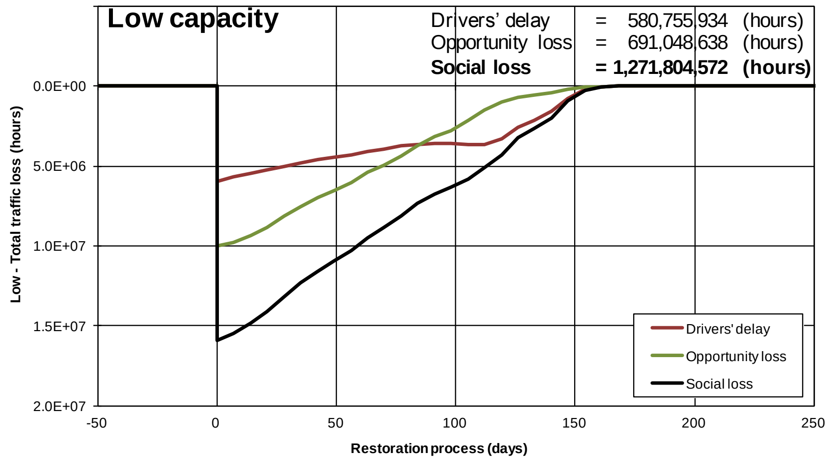


Figure 5.28 Social loss restoration curve: Low capacity & Importance.

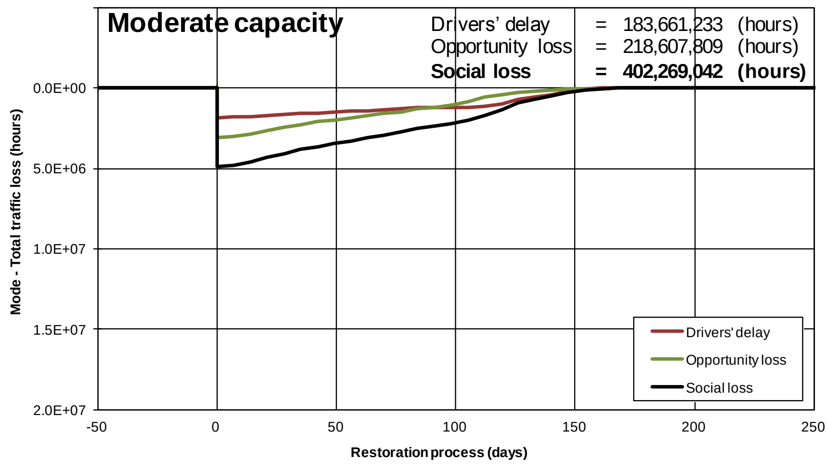


Figure 5.29 Social loss restoration curve: Moderate capacity & Importance.

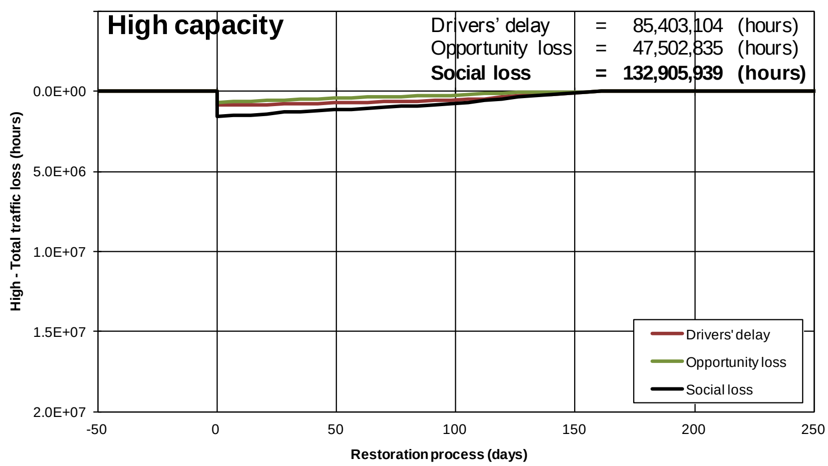


Figure 5.30 Social loss restoration curve: High capacity & Importance.

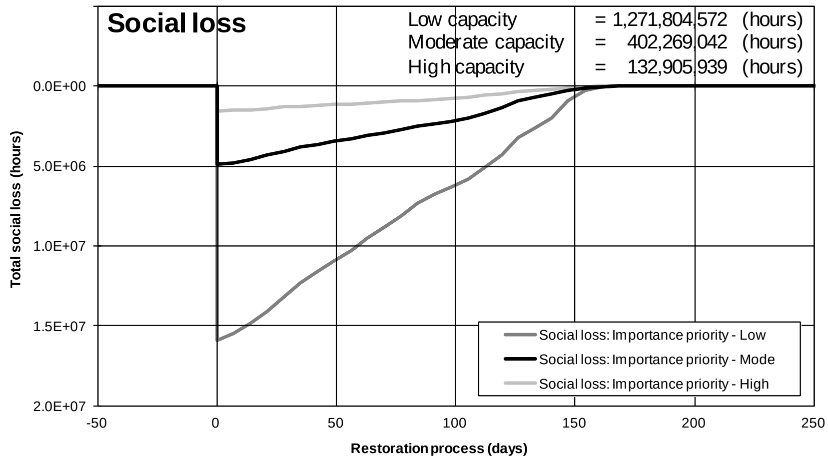


Figure 5.31 Social loss restoration curve: comparison of 3 capacities & Importance.

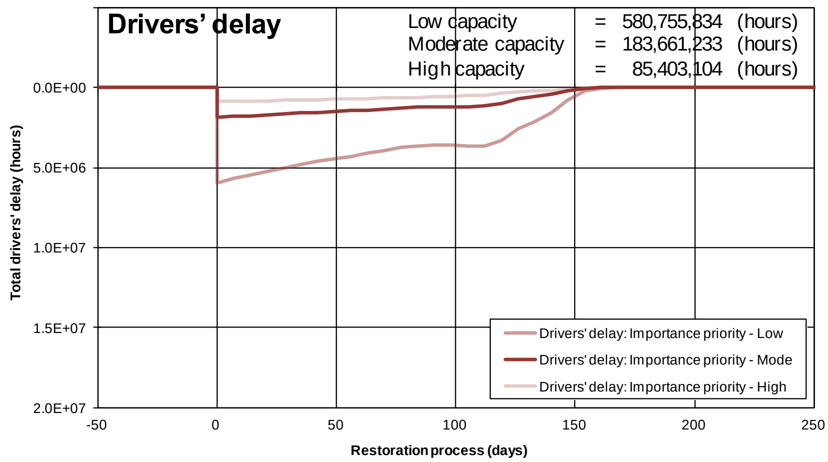


Figure 5.32 Drivers' delay restoration curve: comparison of 3 capacities & Importance.

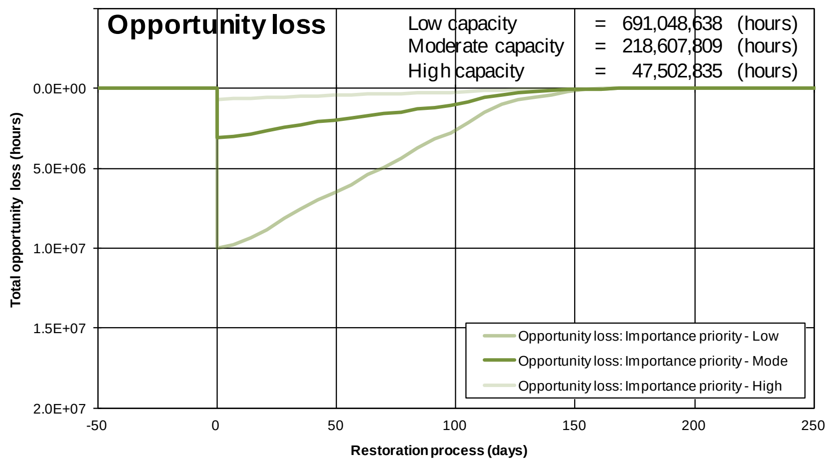
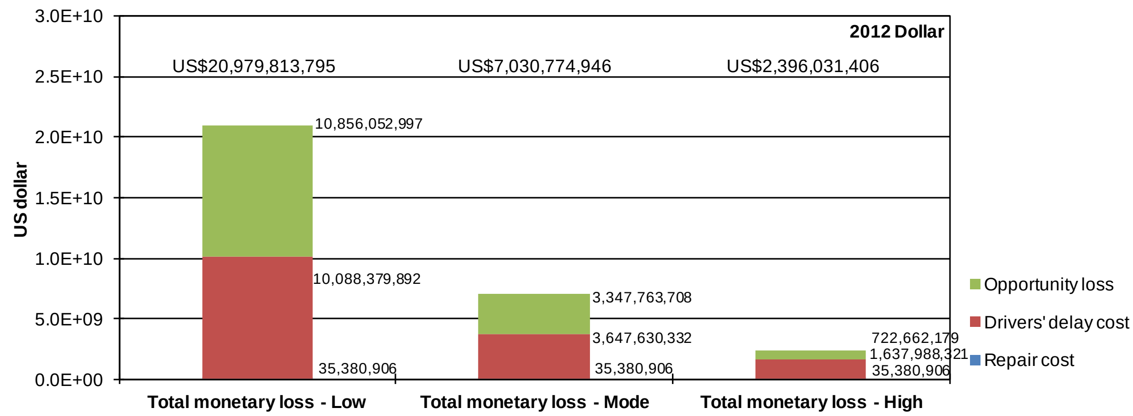


Figure 5.33 Opportunity loss restoration curve: comparison of 3 capacities & Importance.

Table 5.3 Total seismic loss (hours): comparison of 3 capacities & Importance.

Seicmic loss (hours)	Residual traffic capacity level		
	Low	Moderate	High
Total drivers' delay	580,755,934 (1.00) (0.46)	183,661,233 (0.32) (0.46)	85,403,104 (0.15) (0.64)
Total opportunity loss	691,048,638 (1.00) (0.54)	218,607,809 (0.32) (0.54)	47,502,835 (0.07) (0.36)
Total social loss	1,271,804,572 (1.00) (1.00)	402,269,042 (0.32) (1.00)	132,905,939 (0.10) (1.00)

Total social loss comparison of importance priority (economic loss)



Total social loss comparison of importance priority (time loss)

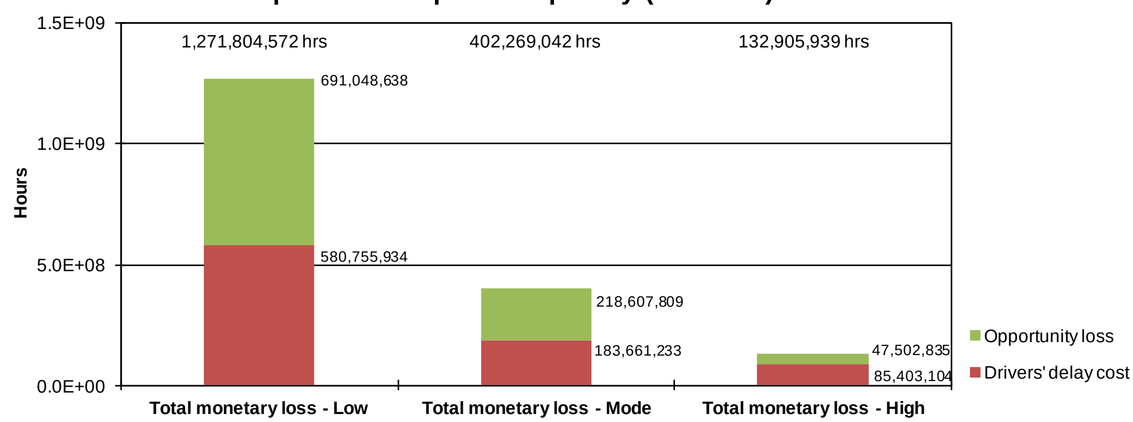


Figure 5.34 Monetary value and total time of social loss of 3 capacities & Importance.

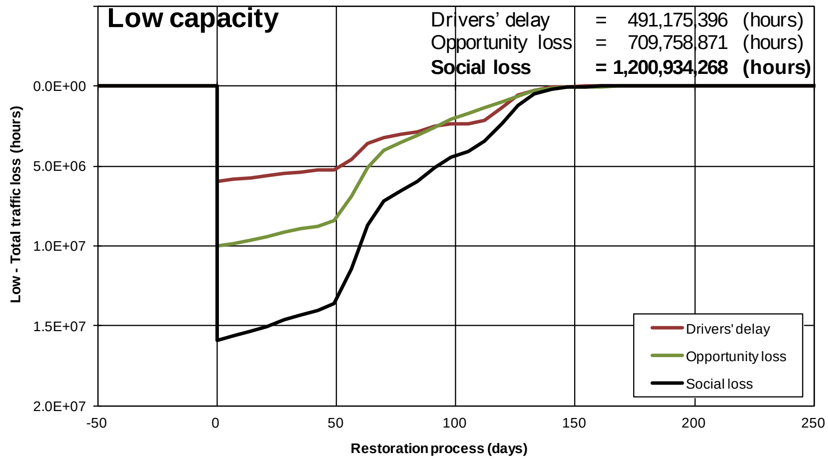


Figure 5.35 Social loss restoration curve: Low capacity & Urgency.

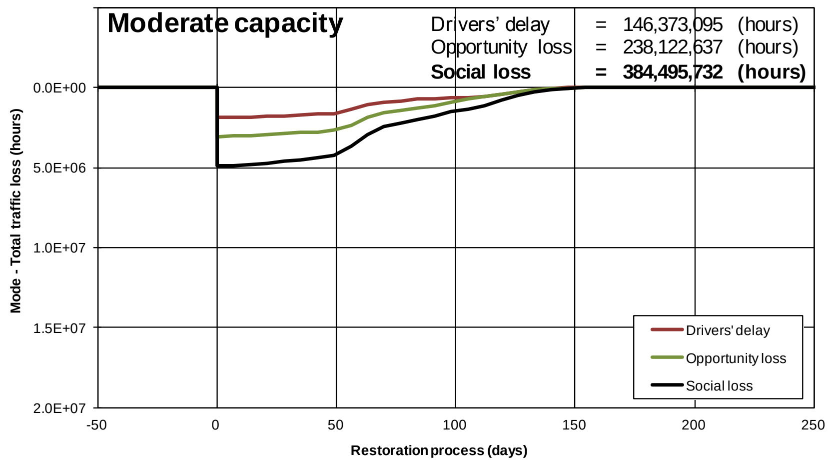


Figure 5.36 Social loss restoration curve: Moderate capacity & Urgency.

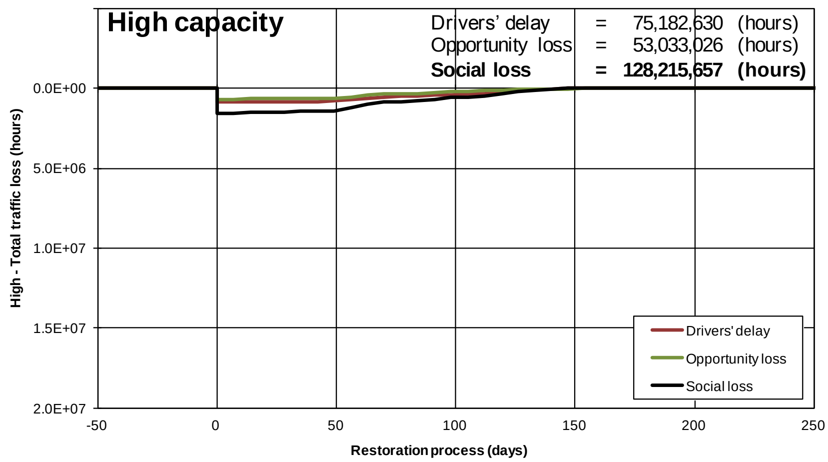


Figure 5.37 Social loss restoration curve: High capacity & Urgency.

Figure 5.38 Social loss restoration curve: comparison of 3 capacities & Urgency.

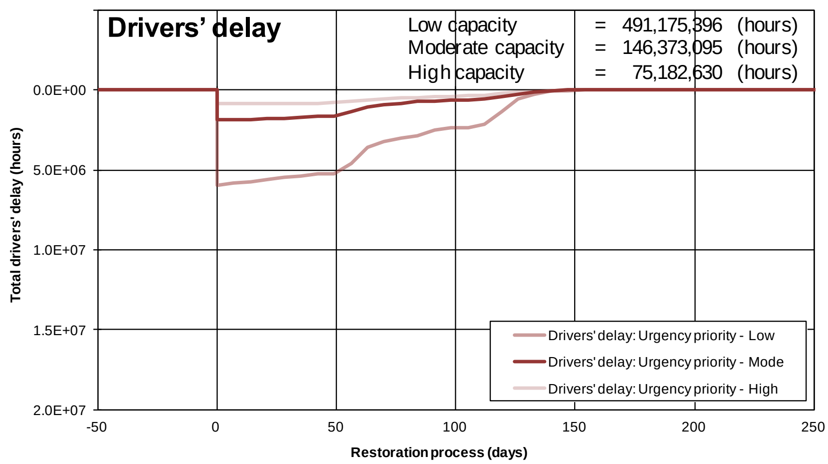


Figure 5.39 Drivers' delay restoration curve: comparison of 3 capacities & Urgency.

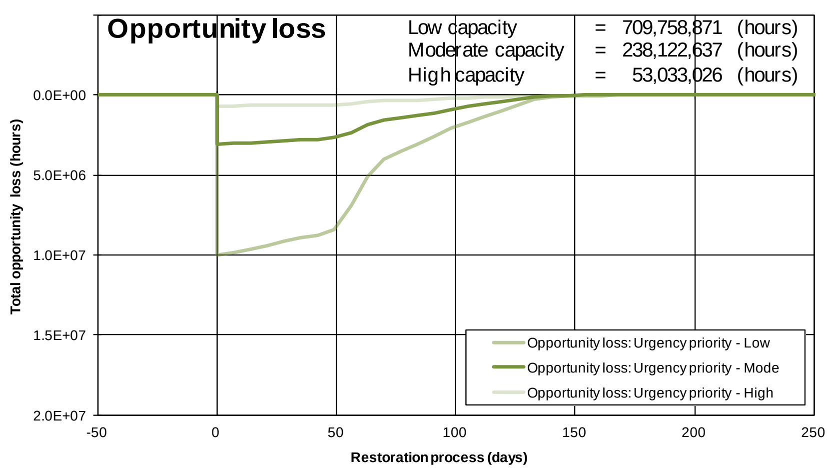
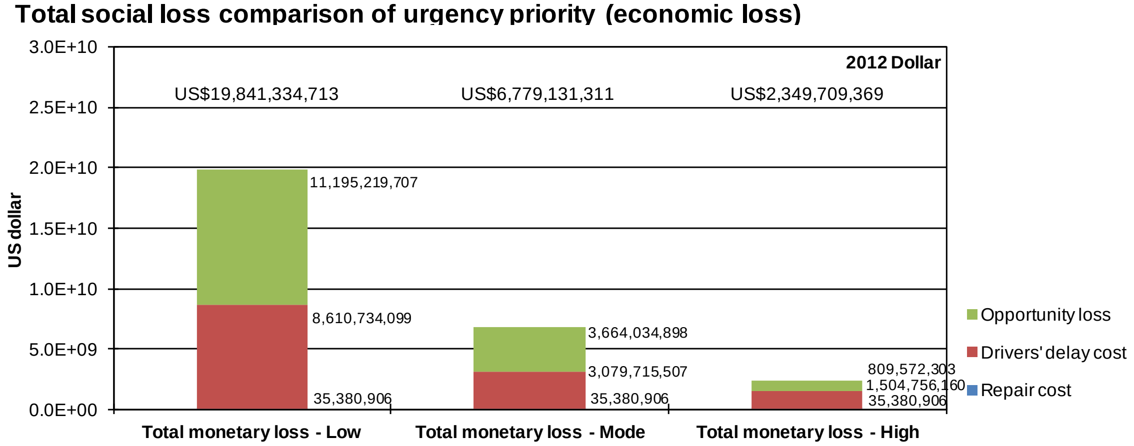


Figure 5.40 Opportunity loss restoration curve: comparison of 3 capacities & Urgency.

Table 5.4 Total seismic loss (hours): comparison of 3 capacities & Urgency.

Seicmic loss (hours)	Residual traffic capacity level		
	Low	Moderate	High
Total drivers' delay	491,175,396 (1.00) (0.41)	146,373,095 (0.30) (0.38)	75,182,630 (0.15) (0.59)
Total opportunity loss	709,758,871 (1.00) (0.59)	238,122,637 (0.34) (0.62)	53,033,026 (0.07) (0.41)
Total social loss	1,200,934,268 (1.00) (1.00)	384,495,732 (0.32) (1.00)	128,215,657 (0.11) (1.00)



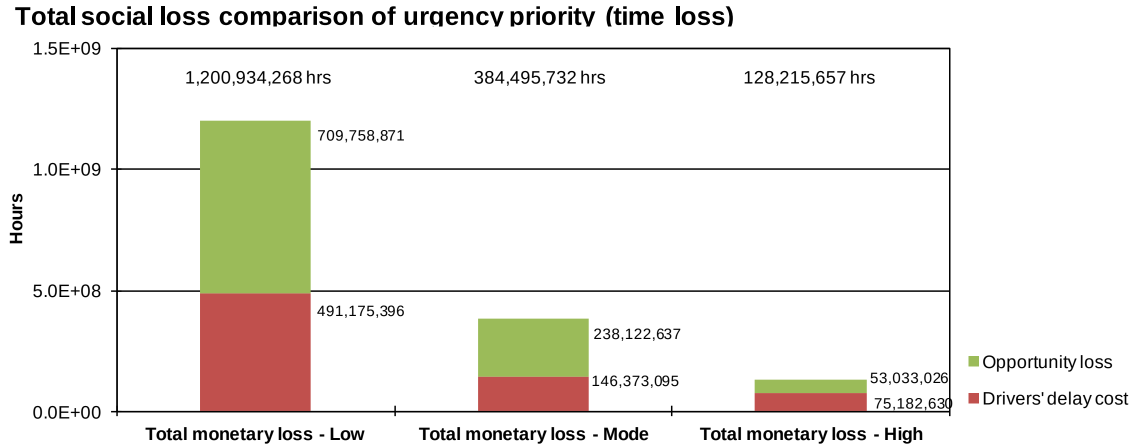


Figure 5.41 Monetary value and total time of social loss of 3 capacities & Urgency.

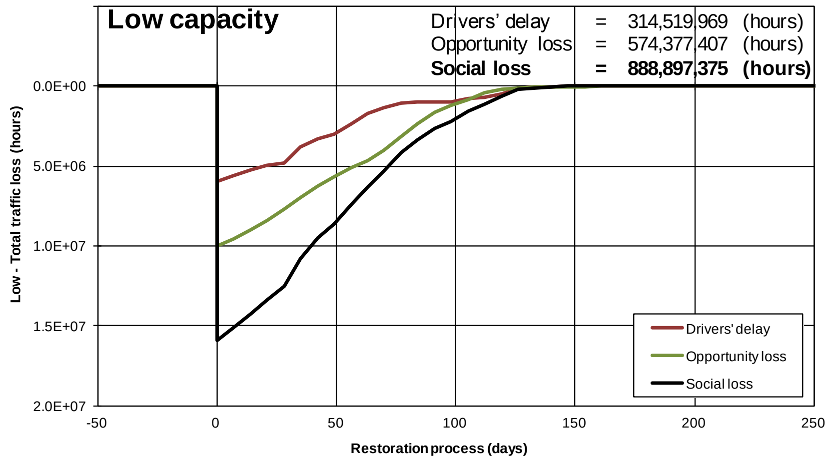


Figure 5.42 Social loss restoration curve: Low capacity & Cost.

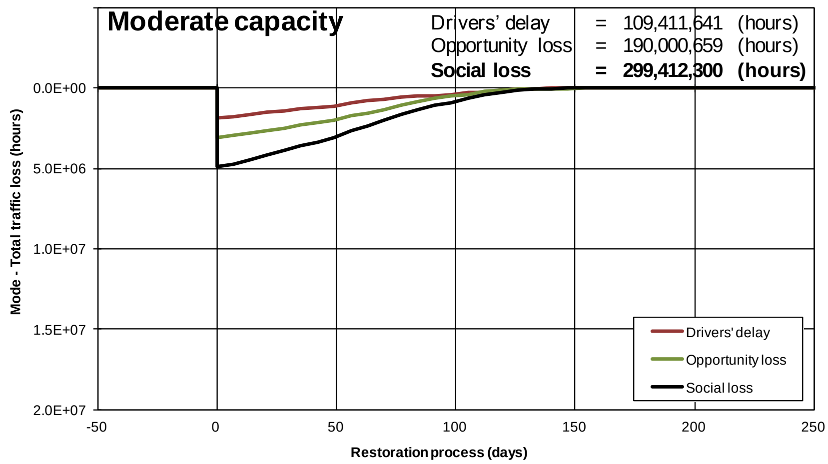


Figure 5.43 Social loss restoration curve: Moderate capacity & Cost.

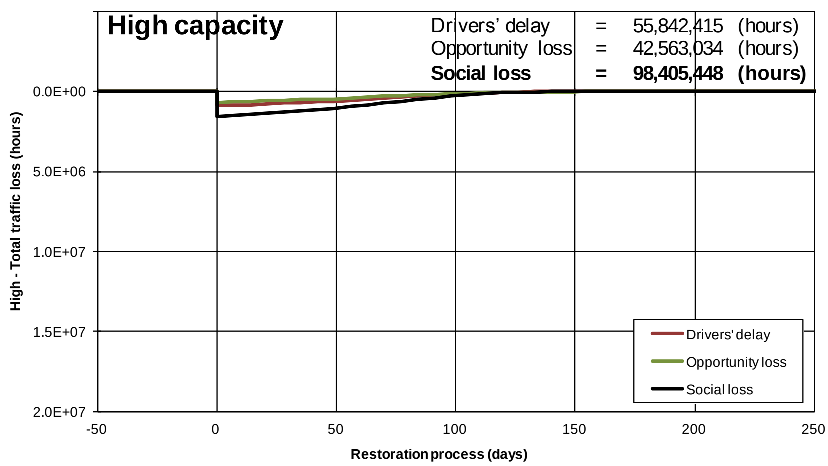


Figure 5.44 Social loss restoration curve: High capacity & Cost.

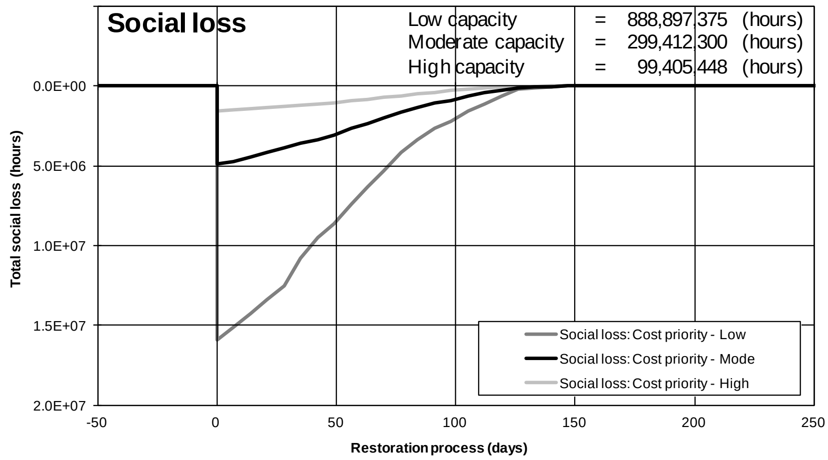


Figure 5.45 Social loss restoration curve: comparison of 3 capacities & Cost.

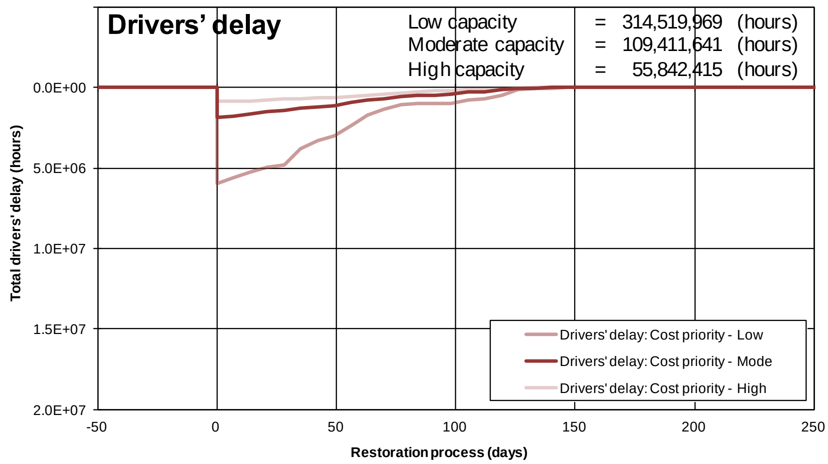


Figure 5.46 Drivers' delay restoration curve: comparison of 3 capacities & Cost.

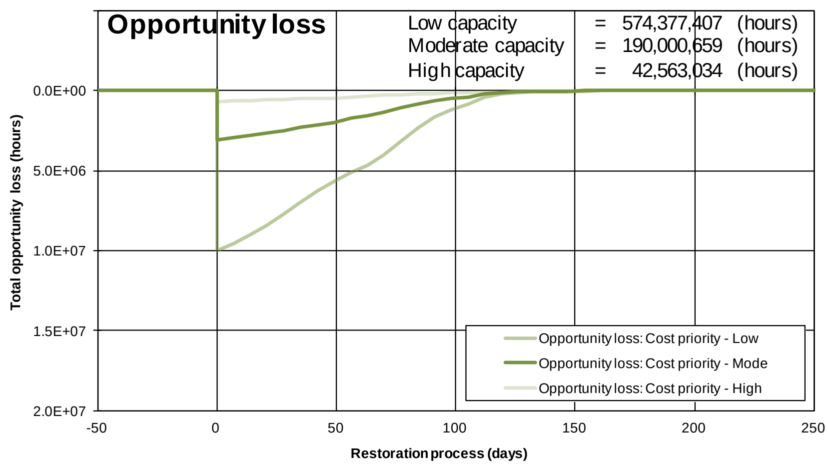
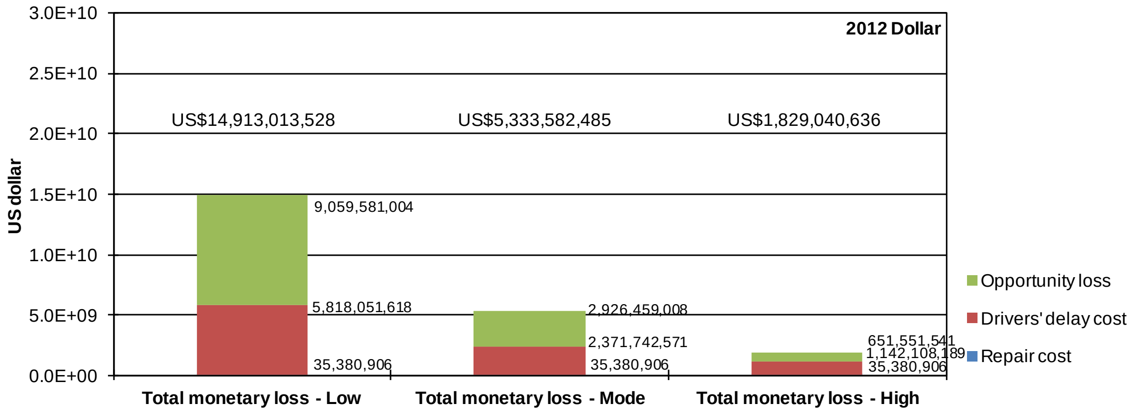


Figure 5.47 Opportunity loss restoration curve: comparison of 3 capacities & Cost.

Table 5.5 Total seismic loss (hours): comparison of 3 capacities & Cost.

Seicmic loss (hours)	Residual traffic capacity level		
	Low	Moderate	High
Total drivers' delay	314,519,969 (1.00) (0.35)	109,411,641 (0.35) (0.37)	55,842,415 (0.18) (0.57)
Total opportunity loss	574,377,407 (1.00) (0.65)	190,000,659 (0.33) (0.63)	42,563,034 (0.07) (0.43)
Total social loss	888,897,375 (1.00) (1.00)	299,412,300 (0.34) (1.00)	98,405,448 (0.11) (1.00)



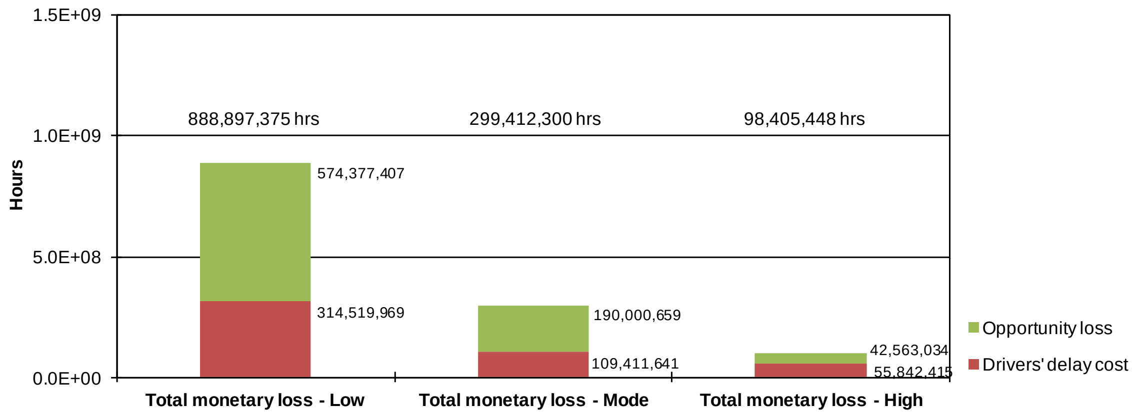


Figure 5.48 Monetary value and total time of social loss of 3 capacities & Cost.

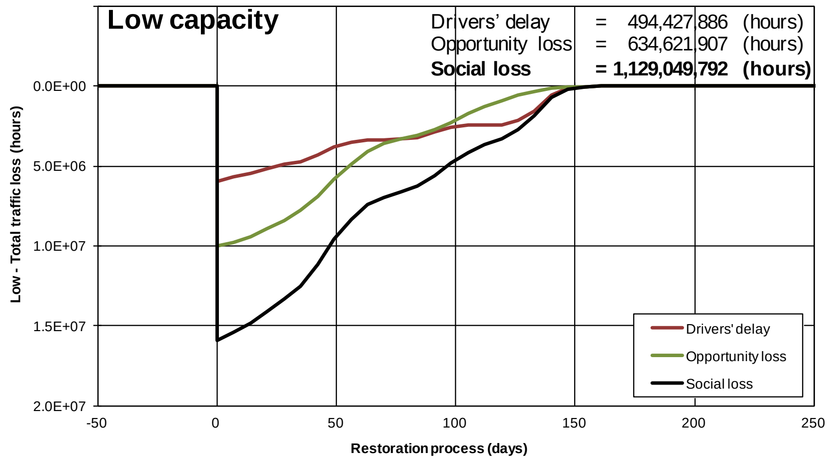


Figure 5.49 Social loss restoration curve: Low capacity & Mix priority.

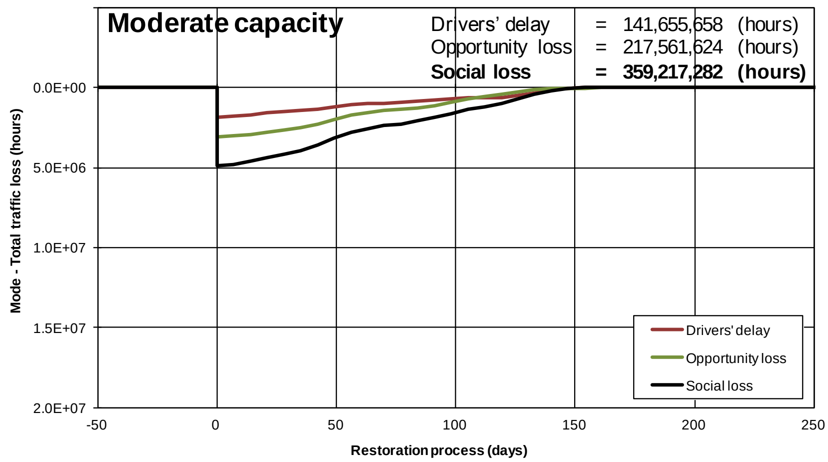


Figure 5.50 Social loss restoration curve: Moderate capacity & Mix priority.

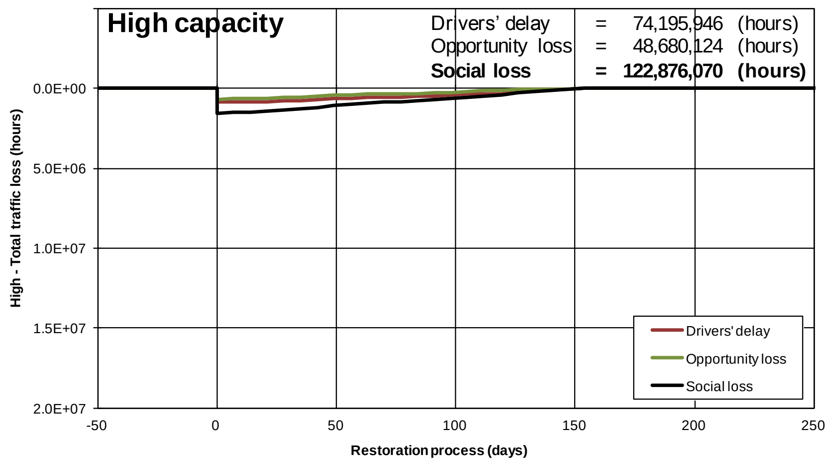


Figure 5.51 Social loss restoration curve: High capacity & Mix priority.

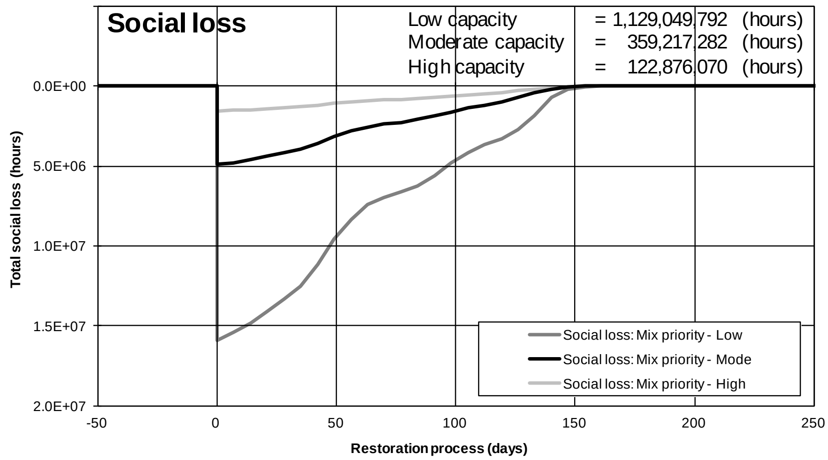


Figure 5.52 Social loss restoration curve: comparison of 3 capacities & Mix priority.

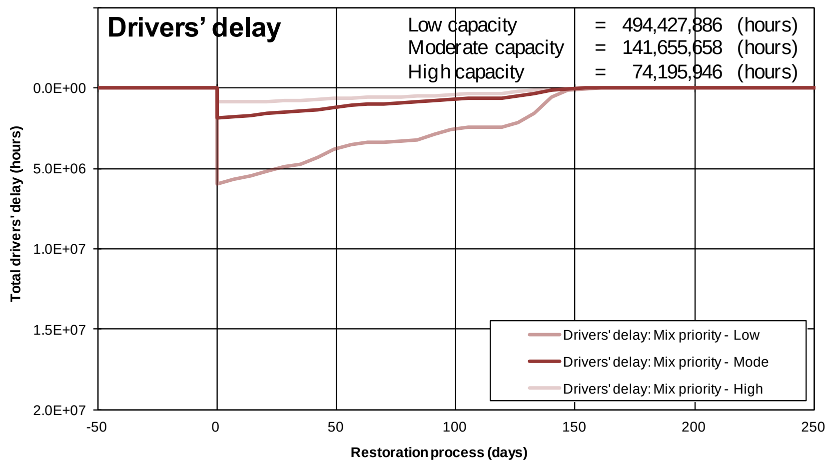


Figure 5.53 Drivers' delay restoration curve: comparison of 3 capacities & Mix priority.

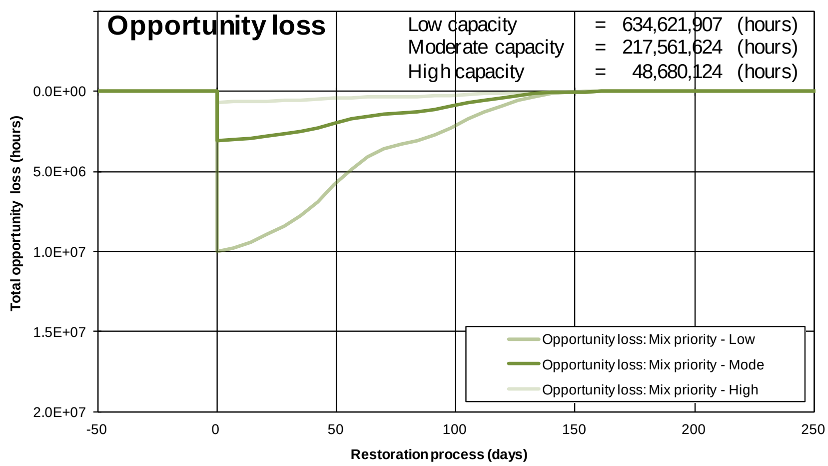
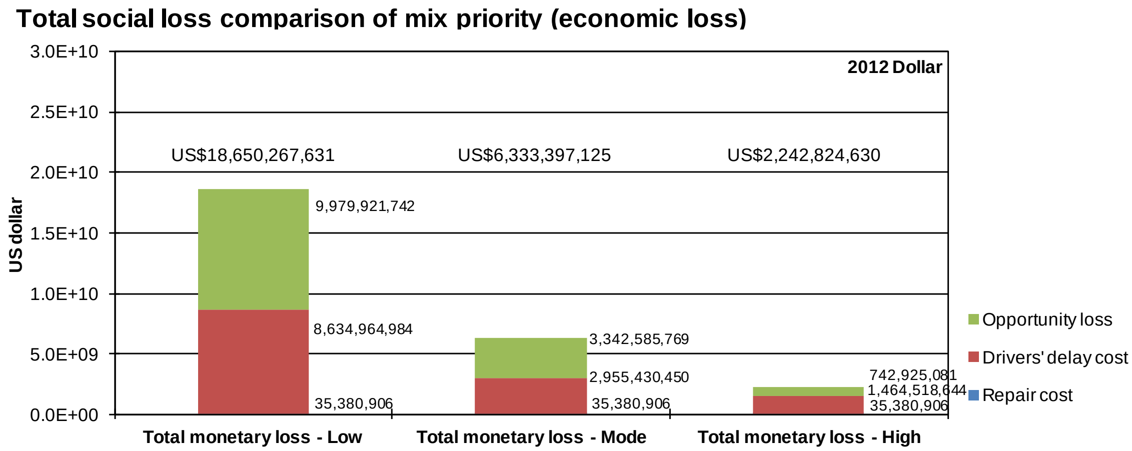


Figure 5.54 Opportunity loss restoration curve: comparison of 3 capacities & Mix priority.

Table 5.6 Total seismic loss (hours): comparison of 3 capacities & Mix priority.

Seicmic loss (hours)	Residual traffic capacity level		
	Low	Moderate	High
Total drivers' delay	494,427,886 (1.00) (0.44)	141,655,658 (0.29) (0.39)	74,195,946 (0.15) (0.60)
Total opportunity loss	634,621,907 (1.00) (0.56)	217,561,624 (0.34) (0.61)	48,680,124 (0.08) (0.40)
Total social loss	1,129,049,792 (1.00) (1.00)	359,217,282 (0.32) (1.00)	122,876,070 (0.11) (1.00)



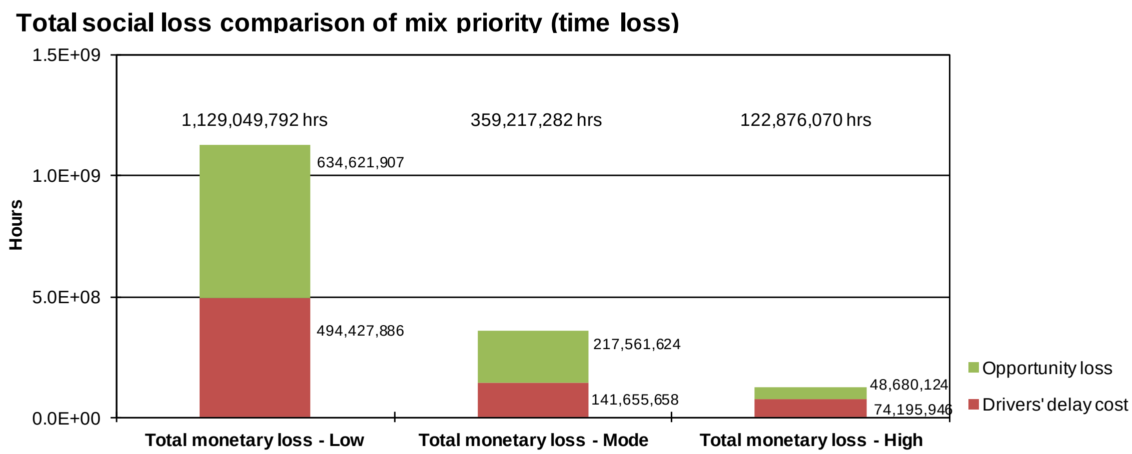


Figure 5.55 Monetary value and total time of social loss of 3 capacities & Mix priority.

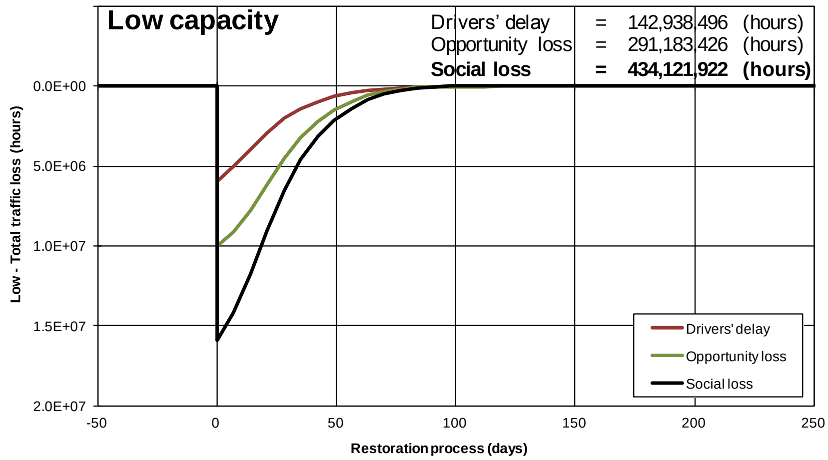


Figure 5.56 Social loss restoration curve: Low capacity & Simultaneous.

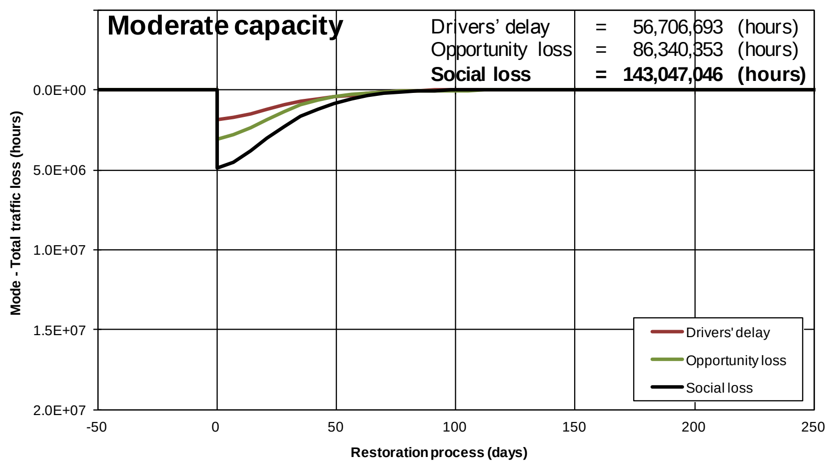


Figure 5.57 Social loss restoration curve: Moderate capacity & Simultaneous.

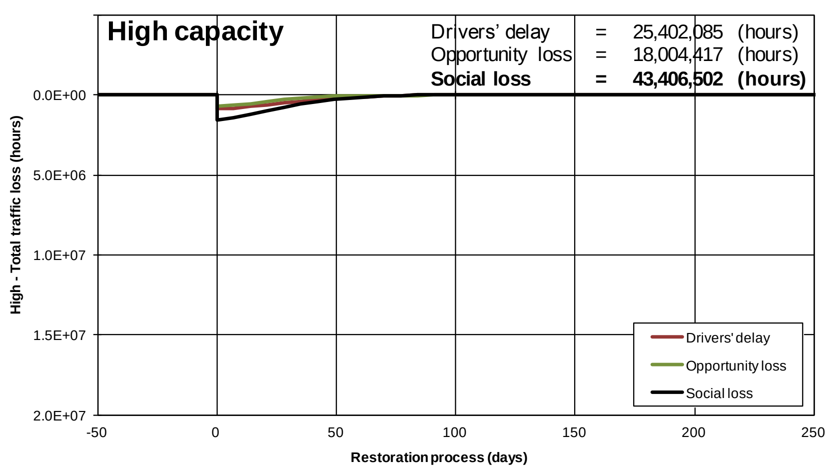


Figure 5.58 Social loss restoration curve: High capacity & Simultaneous.

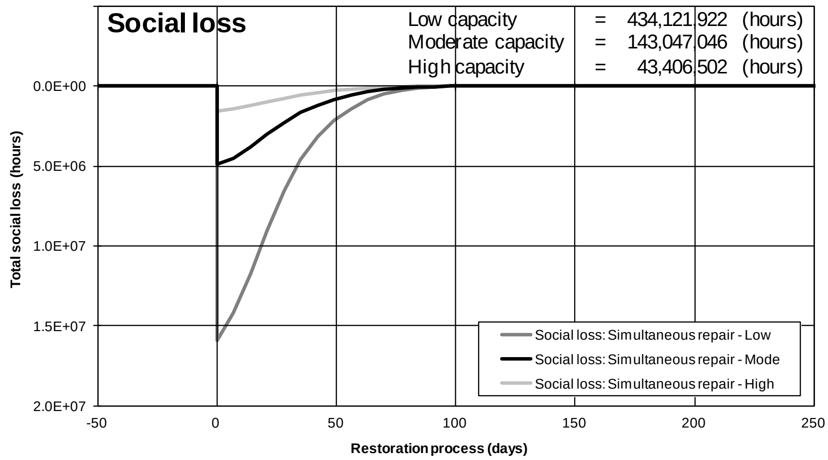


Figure 5.59 Social loss restoration curve: comparison of 3 capacities & Simultaneous.

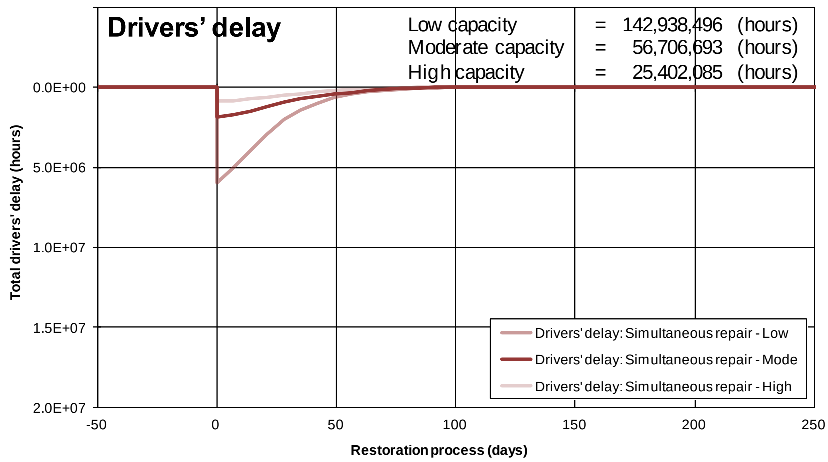


Figure 5.60 Drivers' delay restoration curve: comparison of 3 capacities & Simultaneous.

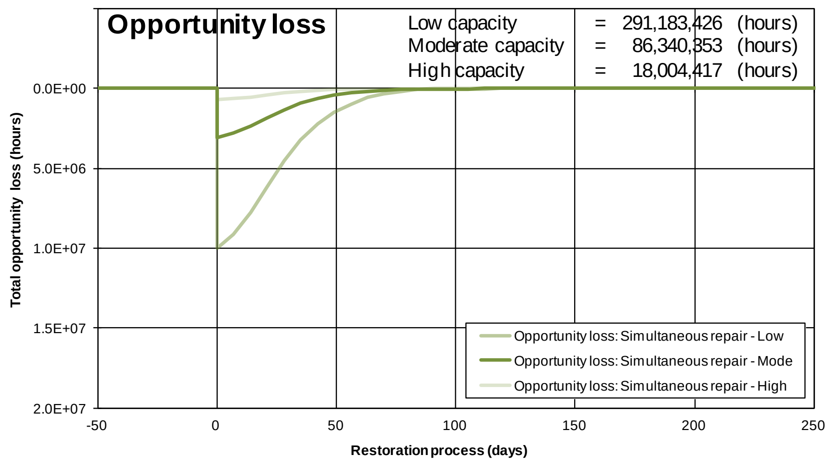
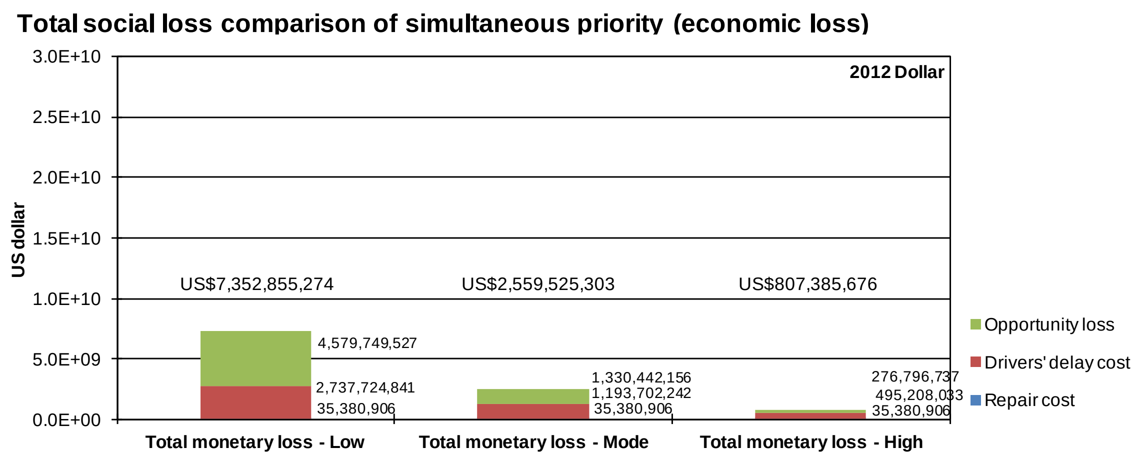


Figure 5.61 Opportunity loss restoration curve: comparison of 3 capacities & Simultaneous.

Table 5.7 Total seismic loss (hours): comparison of 3 capacities & Simultaneous.

Seicmic loss (hours)	Residual traffic capacity level		
	Low	Moderate	High
Total drivers' delay	142,938,496 (1.00) (0.33)	56,706,693 (0.40) (0.40)	25,402,085 (0.18) (0.59)
Total opportunity loss	291,183,426 (1.00) (0.67)	86,340,353 (0.30) (0.60)	18,004,417 (0.06) (0.41)
Total social loss	434,121,922 (1.00) (1.00)	143,047,046 (0.33) (1.00)	43,406,502 (0.10) (1.00)



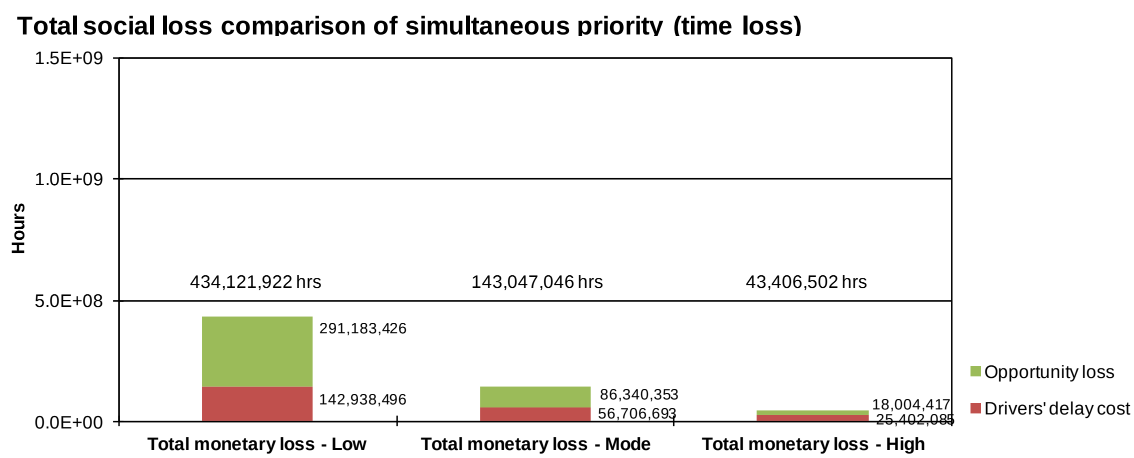


Figure 5.62 Monetary value and total time of social loss of 3 capacities & Simultaneous.

5.8 Practical utilization

An application example is demonstrated by applying a potential scenario earthquake in this region to the developed model throughout this chapter, and the whole analysis process and the results regarding post-earthquake recovery of highway network performance are shown. In this section as the last of this application study, a way of practical and effective utilization of this simulation methodology is suggested for convenience of decision-makers/policy-implementers who might not be familiar with fields of civil engineering and probabilistic simulation by taking several results simulated on importance priority order and moderate residual traffic capacity.

The restoration curves which express temporal development of repaired bridges are illustrated in Figure 5.63. Both total number of damaged bridges and that of each damage state are depicted over the entire restoration period. This restoration curve clearly represents physical recovery process of highway network from seismic damage, so this does not mention anything about traffic performance degradation in a direct way. However, the achievement of bridge reconstruction works corresponding to damage status at a specific time can be explored by this restoration curve. For example, half of damaged bridges are rehabilitated by about Day 110 and there are still 8 collapsed bridges, 56 major damaged bridges, 93 moderate damaged bridges and

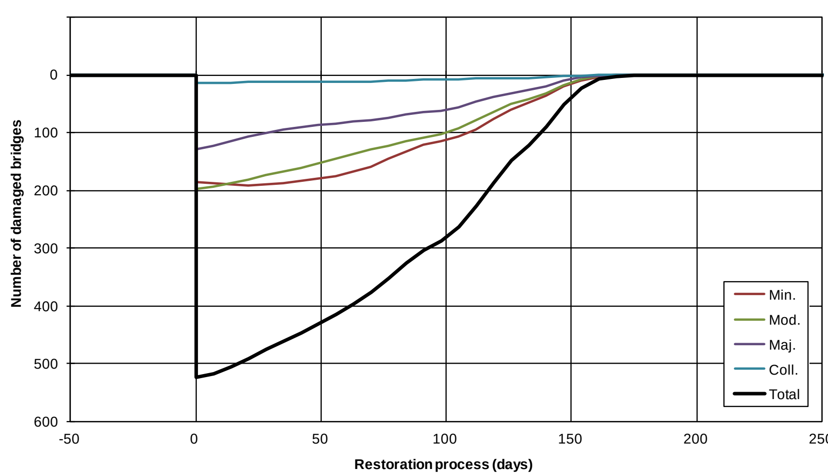


Figure 5.63 Bridge restoration curves: Importance & Moderate.

107 minor damaged bridges at that time. On the other hand, 48 reconstruction works of damaged bridges are completed within first 4 weeks, and it is only 9% accomplishment of the total. Thus, a physical recovery target such as bridge reconstruction achievement can be specifically established for a lean construction work progress by investigating this simulated bridge restoration curves.

The restoration progresses of damaged links are drawn in Figure 5.64, and both total and individual damage states are illustrated in this graph. This restoration curve also presents physical recovery process of highway road segments, and the link damage depends directly on the bridge damage status. The link damage state straightforwardly effects on the residual traffic capacity rate described in the next paragraph. Since the worst damaged bridge represents the damage state of link, the number of major damaged link is the greatest number at the beginning and accounts for 46% of the total (i.e., total is 256 and major is 114). There is not particularly similar trend between link damage recovery and bridge damage restoration because the link damage is decided by only spatial distribution of bridge damage based on bottleneck hypothesis in this methodology. However, this restoration curves are useful for getting an overview of roadway restoration progress. For instance, the collapsed link number does not decrease quickly

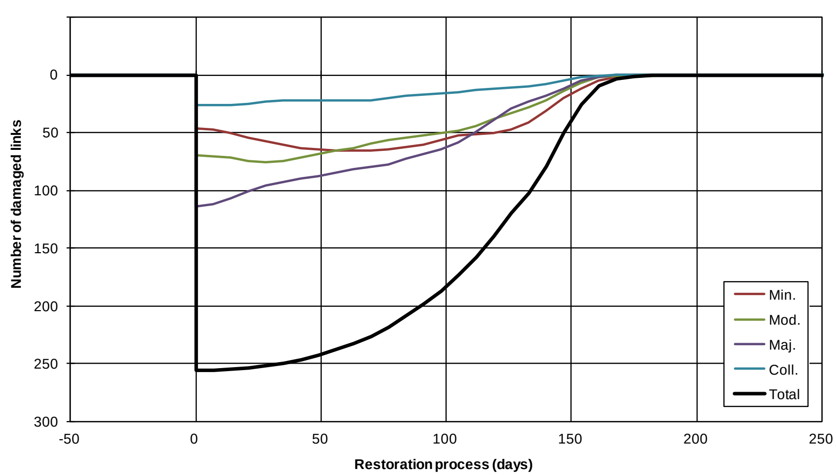


Figure 5.64 Link restoration curves: Importance & Moderate.

and they are repaired very gradually. At the same time, the major damaged links are restored rapidly. Therefore, traffic performance affected by link damage may go back to normal pointedly from the standpoint of redundancy of entire highway network though the speed of recovery work for collapsed link is slow.

The restored number of links with degraded traffic capacity is expressed with lapse time by Figure 5.65. The traffic capacity of links with collapse, major and moderate damage is impaired to some extent, but the minor damaged link is assumed to be able to keep 100% capacity for transportation capability of alternative routes. Therefore, this graph shows the restoration progress of links suffering collapse, major and moderate damage. The links with degraded capacity have direct impact on highway traffic functionality. It is true that this restoration curve cannot explicitly represent exact degradation of highway performance of this whole model. However, this curve gives a good indication for studying a relationship between physical recovery (i.e., physical reconstruction) and performance recovery (i.e., traffic network recovery). For example, half of total links impaired capacity are restored on about Day 115, and highway performance such as drivers' delay and opportunity loss is recovered 50% by about Day 125 and Day 75, respectively, as shown in Figure 5.66. Thus, some kinds of similarities about

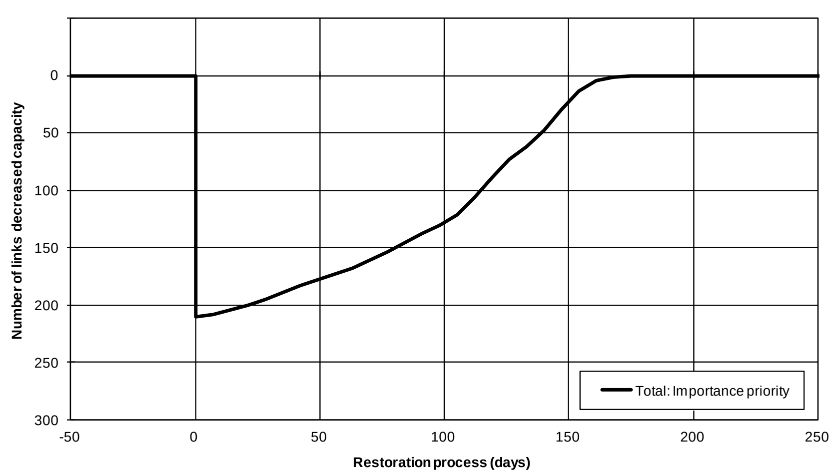


Figure 5.65 Link capacity restoration curves: Importance & Moderate.

restoration progress and curve shape are recognized in both restoration processes.

In Figure 5.66, the social loss restoration curve in terms of highway network performance is indicated with progresses of drivers' delay restoration and opportunity loss restoration. In addition, restoration curves divided into 6 trip types are derived for each performance restoration curve and are shown in Figure 5.67 to Figure 5.69, respectively. The total performance degradation is fully restored on about Day 175 (i.e., 5.8 months) as shown by black line in Figure 5.66. The amount of opportunity loss is more than that of drivers' delay during the first half term, but time losses of drivers' delay and opportunity loss are reversed on about Day 90. This is because the recovery speed of opportunity loss is very fast compared with the gradual recovery of drivers' delay. This means that the repair order implemented here can quickly boost the declined traffic demand (e.g., trip motivation) but might not be able to contribute effectively to restitute increased drivers' time. Indeed, 62% of opportunity loss is recovered at the time of Day 90 but drivers' delay is rehabilitated just 35% at the same time. Since both types of restoration time passage are simulated specifically, they can help for establishing reconstruction plan and repair strategy with consideration of target time. For example, the drivers' delay restoration curve should be intensively studied if policy maker prefers achievement of traffic flow recovery,

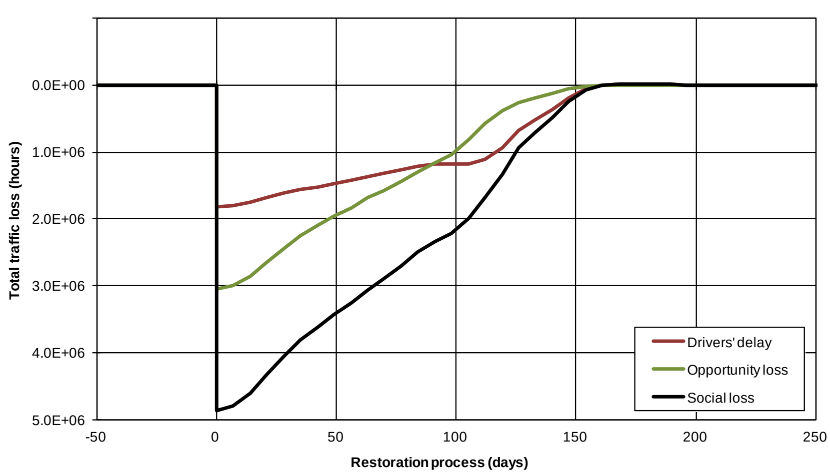


Figure 5.66 Social loss restoration curves: Importance & Moderate.

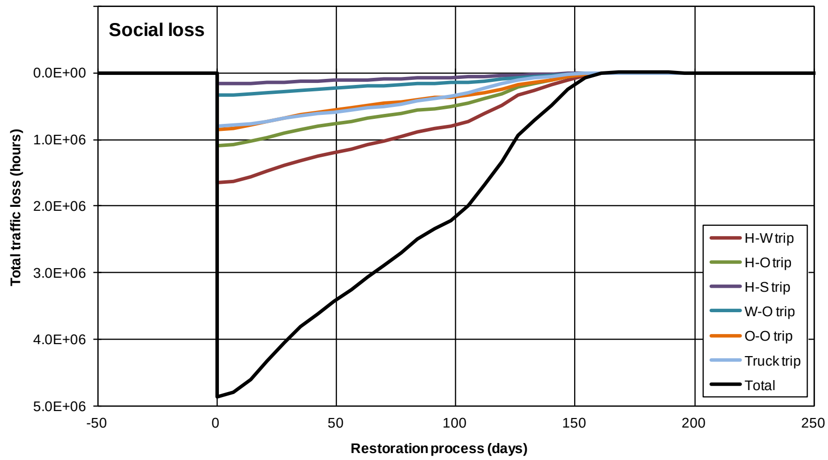


Figure 5.67 Social loss restoration curves of 6 trips: Importance & Moderate.

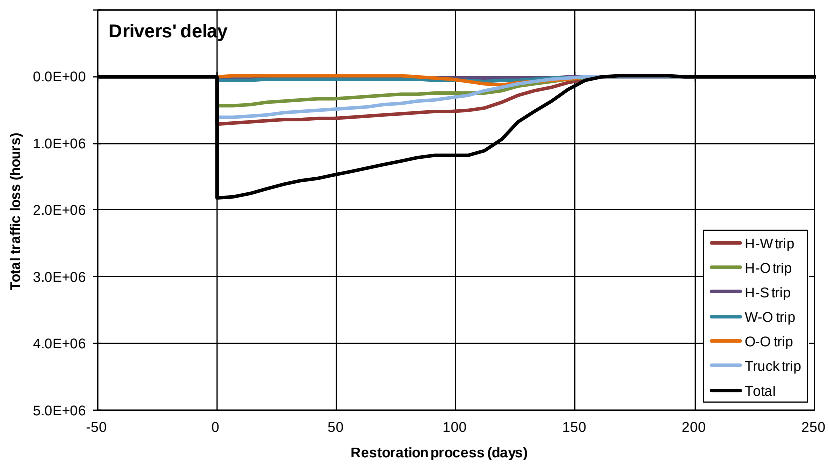


Figure 5.68 Drives' delay restoration curves of 6 trips: Importance & Moderate.

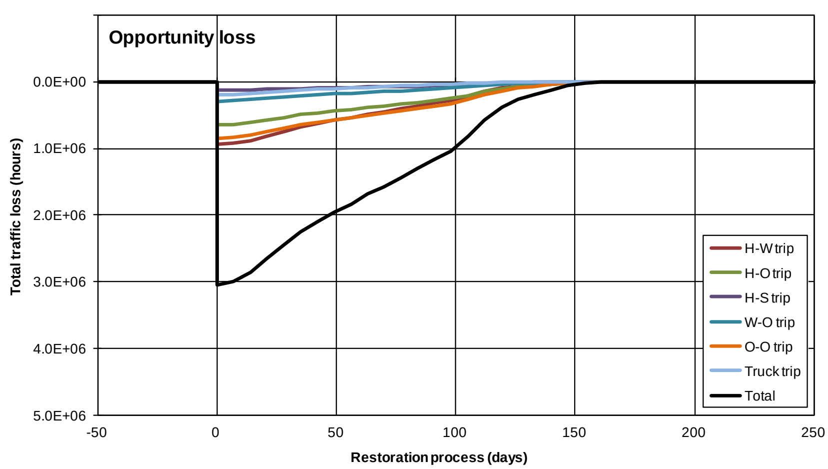


Figure 5.69 Opportunity loss restoration curves of 6 trips: Importance & Moderate.

the restoration process of opportunity loss should be investigated in depth if decision maker focuses on quick reactivation of vehicle trips, and the social loss recovery process should be deeply explored if both drivers' time and traffic demand are equally considered for decision-making to restore highway network system. The restoration curves of each trip type can be separated from the total as shown in Figure 5.67 to Figure 5.69, and the impacts of each trip's recovery to the total performance level can be examined. In this case, the rate of home-work trip is large to the total loss of both drivers' delay and opportunity loss, and its rate is about 35% at the beginning of restoration period. The second one is the loss of home-other trip, and the portion of that to the total is about 22% at the beginning. Here, the loss of truck trip effects 16% influence on the total amount. And, the rate of opportunity loss caused by truck trip type is very small though that of drivers' delay is quite large relatively. This trend lasts for the entire restoration period. The exact cause cannot be specified by this model, but possible reasons are thought that the less cancellation of truck trips make additional driving time large or severe damages of a part of links which trucks use regionally (e.g., route close to container port or logistics area) have drivers' delay more. Thus, the detailed progress of recovery process about traffic performance are scrutinized by social loss restoration curve, and this simulated result can be valuable information for making decision to mitigate total seismic loss during restoration period (i.e., enhancement of highway network resilience).

The monetary value of total social loss without bridge repair cost and its relative rates are calculated in Figure 5.70 and Figure 5.71, and the hourly amount of total social loss and its relative rate are indicated in Figure 5.72 and Figure 5.73. The total social economic loss without bridge repair cost is US$ 6,995,394,040, and the total social time loss is 402,269,042 hours. The indicated total loss is divided into business/non-business and trip types. The proportion of

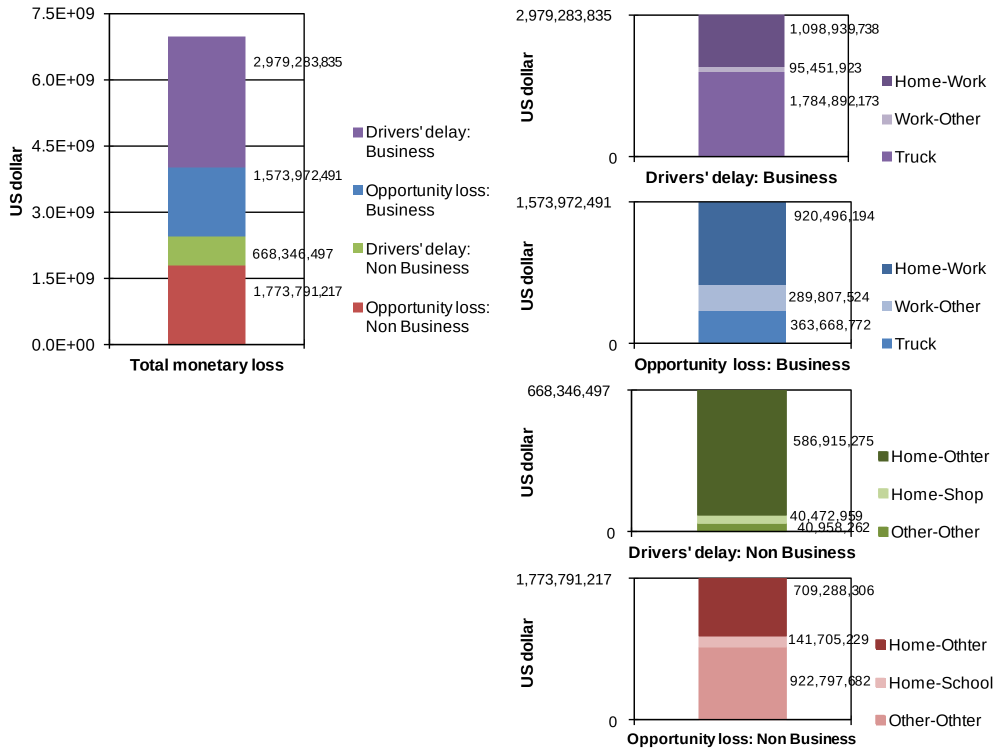


Figure 5.70 Monetary value of social loss (US$): Importance & Moderate.

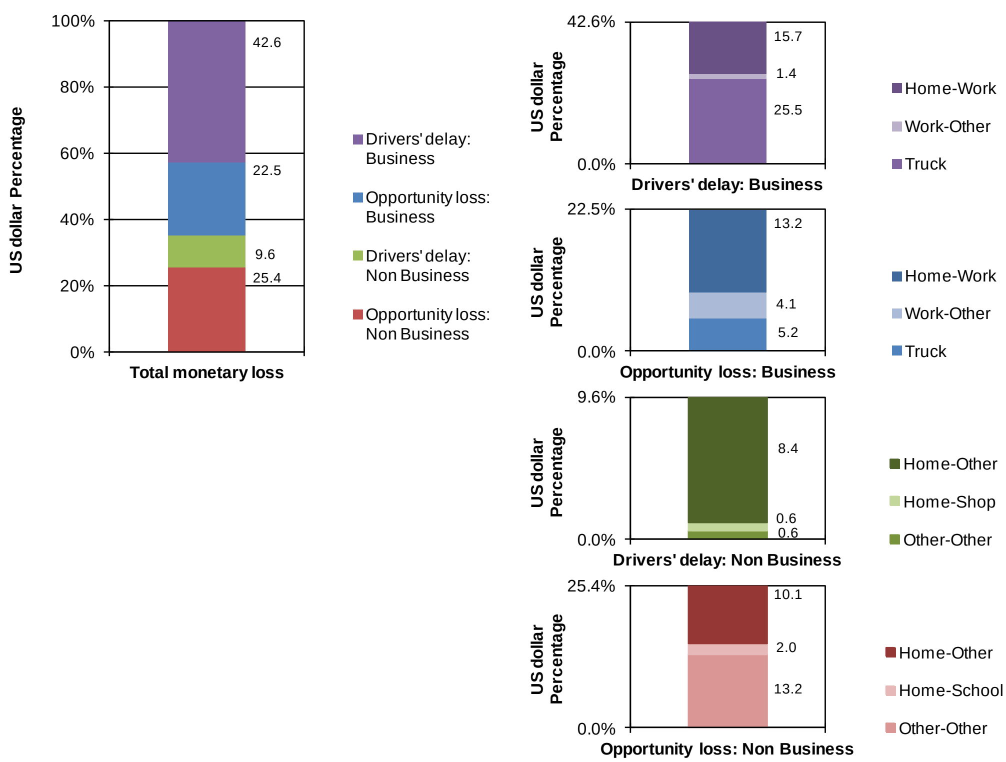


Figure 5.71 Monetary value of social loss (rate): Importance & Moderate.

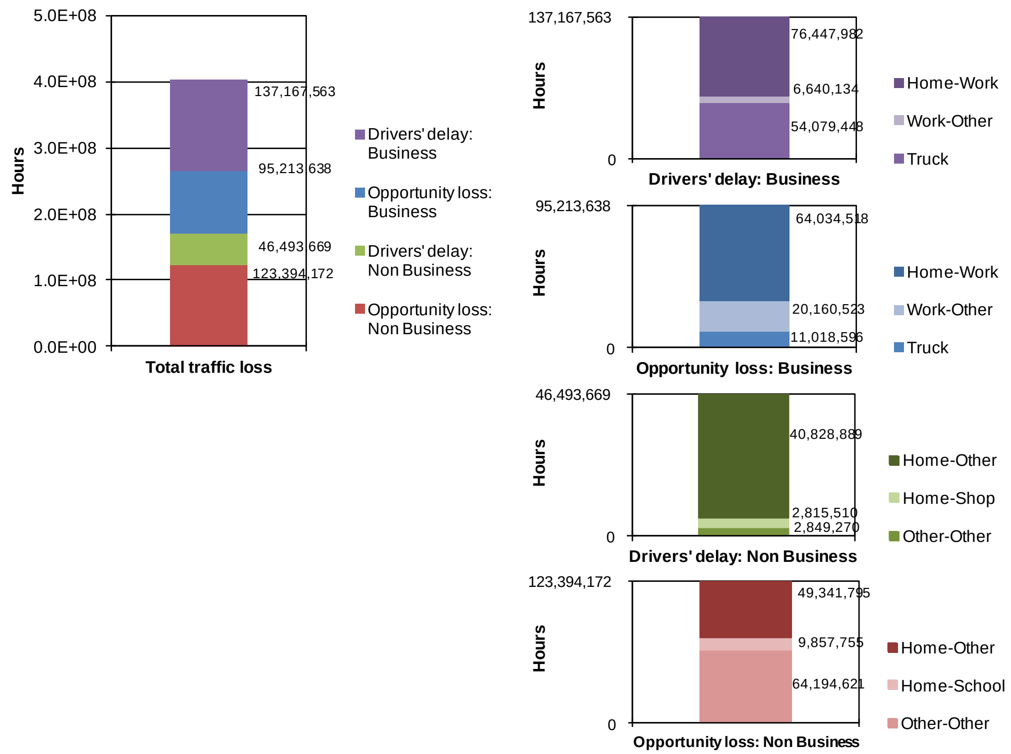


Figure 5.72 Total time of social loss (hours): Importance & Moderate.

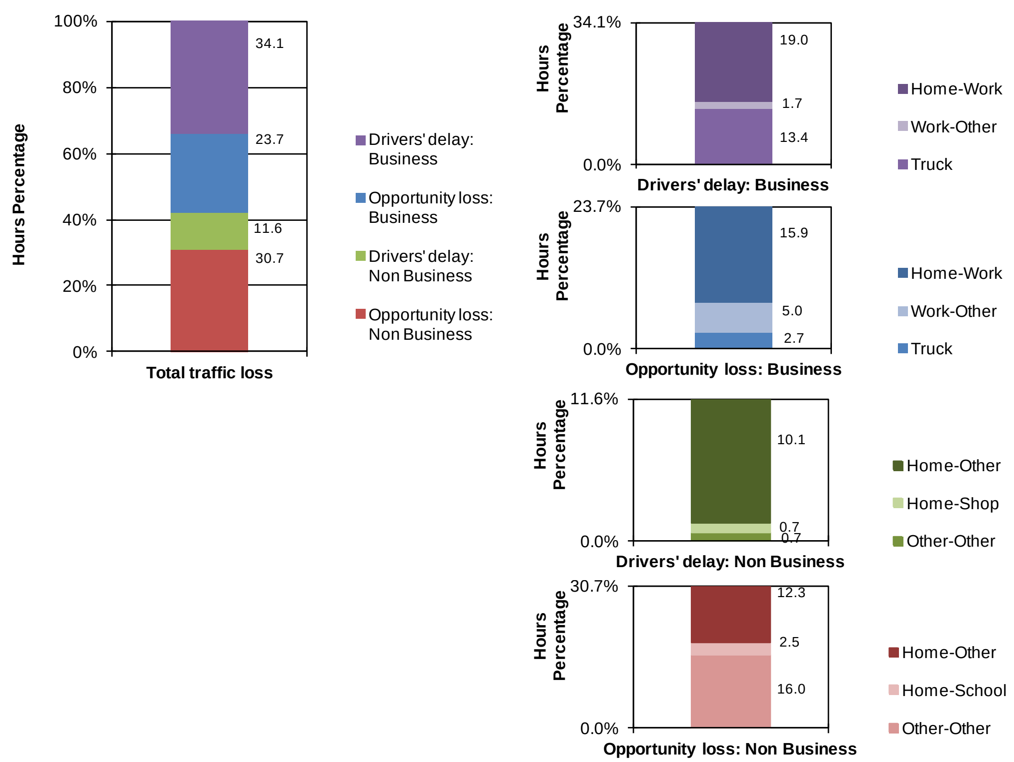


Figure 5.73 Total time of social loss (rate): Importance & Moderate.

business loss is 58% in time loss but it increases 65% in economic loss. This is because the unit economic valuation of truck trip, US$ 28.70, is more than double of automobile trip value, US$ 12.50. In fact, the rate of truck trip loss also increases 16% in time loss to 31% in economic loss. This rate in economic loss is the largest percentage in 6 trips, and the total economic loss of truck trip is estimated as US$ 2,148,560,945. Therefore, maybe, the traffic volume of heavy truck routes should be considered as a criterion for prioritizing repair order to mitigate economic loss. The second largest economic loss is US$ 2,019,435,932 of home-work trip, and its rate to total is 29%. The third one is US$ 1,296,203,581 of home-other trip, and its rate is 18.5% of total economic loss. By focusing on these largest three trips, the total rate of these economic losses accounts 78.5% of whole amount. Then, the rate of these three trips total of drivers' delay in monetary value is about 50%, and that of opportunity loss is about 28.5%. From these results, a repair order to reconstruct links relating to these three trips first with consideration of original importance priority might be the more effective strategy for decreasing total economic loss in this case. Additionally, the links which are dominated by the largest two trips should be repaired first if business loss has to be decreased first compared to non-business loss and vice versa.

Chapter 6

Conclusions and future works

6.1 Conclusions

This dissertation focuses on simulating a realistic restoration process of highway transportation network suffered seismic damage with consideration of repair prioritization for contributing decision-making to mitigate post-earthquake damage and to enhance seismic resilience. This research is conducted by multidisciplinary study approach combining with earthquake engineering, structural engineering, transportation engineering, probabilistic technique, social science and economy. The main challenges and conclusions of this research are summarized as discussed in detail below.

Novel functions and original algorithms are integrated in the highway transportation network model developed in previous research. Firstly, an algorithm for prioritizing repair order of damaged bridges is developed, and the repair order is decided systematically and numerically by using Analytic Hierarchy Process based on several criteria of prioritization. This algorithm can calculate priority value of each damaged bridge mathematically by using weight values of criteria and bridges provided hierarchially. Those weight values are decided structurally and functionally with consideration of bridge characteristics, damage status and highway performance such as traffic volume. Since a prioritized repair order can be obtained explicitly, this unambiguous and convictive process to give a priority for repair order is profitable for transparent decision-making. Secondly, a methodology for replicating reconstruction progress is built by constraining repair advancement along actual work process under post-earthquake situation. The regional limited labor under post-earthquake circumstance and the necessary workforce for repairing damaged bridges are considered as reconstruction constraint for this scheme. The necessary number of bridge construction workers is estimated on the basis of statistical data surveyed by United States Department of Labor and Caltrans report of Northridge earthquake about work environment. The regional maximum labor for repair work evaluated by statistical records of both organizations is verified by a calibration study with actual records at Northridge earthquake. Applying construction labor as constraint is more realistic than using the monetary budget which can be paid after repair completion, so this methodology can reproduce bridge reconstruction progress practically. Thirdly, an original bridge restoration model following Markov Chain process is created for simulating probabilistically repair progress through Monte Carlo technique. This model updates probability of bridge damage transition and repair completion corresponding to damage status at a certain time interval. The damage transition probability matrix for representing repair progress in Markov Chain process is identified through a calibration investigation based on post-earthquake recovery records of collapsed bridges at Northridge earthquake, and the adequacy of the model is verified. The existing bridge restoration models, Uniform distribution model and Normal distribution model, in addition to this developed model are applied to the simulation for comparison investigation, and the advantage of Markov Chain process morel is confirmed. Fourthly, the social loss which is sum of drivers' delay and trip opportunity loss due to impaired highway traffic performance is divided into business loss and non-business loss. More specifically, the 6 trip types of Origin-Destination matrix are classified according to trip purposes, which means that home-work, other-work and truck trip are categorized as business trip and home-other, other-other and home-shop are considered as non-business trip. Each loss is estimated separately, and an impact of business loss to total seismic loss can be then explored. Also, restoration processes of both trip types can be expressed specifically as the form of restoration curve. This categorized loss estimation can work well for preparing post-earthquake operation for both regional industry world and societal activities. Lastly, these developed algorithms are then incorporated in the traffic assignment analysis of highway network, and the restoration process is estimated on each time during the entire recovery period. Social loss, drivers' delay and trip opportunity loss are then evaluated as performance of highway traffic network, and these simulated seismic losses are represented in both time domain (i.e., hours) and economic standpoint (i.e., US dollar). Additionally, the total performance loss can be separated into 6 trip types or two groups such as business trip and non-business trip for convenience to establish a detailed recovery strategy.

The model verification works are implemented based on Northridge earthquake records and estimations. This is because a lot of various documented data and researches about Northridge earthquake have been published and this model is built on highway network in Los Angeles and Orange counties where this earthquake caused disastrous damage. The entire simulation is done by applying actual bridge damages, actual earthquake intensity distribution, repair order estimated on importance priority assumed by actual records, reconstruction labor constraint calibrated by Northridge earthquake experience, three bridge restoration models and three levels of residual traffic capacity. Then, the appropriateness of Markov Chain process model and moderate level of residual traffic capacity is verified by comparative examinations with the published estimation of economic loss and time loss regarding traffic related impacts at Northridge earthquake. Since the deviations of end products (i.e., social loss) derived from difference of bridge restoration model and residual traffic capacity level are not small in both restoration progress and total economic loss, the fact that the model has been verified by actual records is very meaningful for putting the model to practical use.

The applicability of the established analysis framework is demonstrated by simulating entire processes by applying a regional potential scenario earthquake, Newport-Inglewood fault earthquake Mw7.1 in chapter 5. Post-earthquake restoration processes corresponding to 6 prioritized repair orders are evaluated, and the corresponding social losses as highway network performance are obtained. The difference of total seismic loss (i.e., both money and time) can show the different level of resilience according to repair prioritization, and the temporal transitions of each order's restoration can be also compared one another. Especially, the detailed recovery progress as time passes can be scrutinized for tracking step-by-step situation of both physical bridge repair and functional traffic recovery. Therefore, decision makers can plan various damage mitigation strategies by focusing on not only full completion time but also partial recovery at a certain time. In addition, sensitivity analysis according to residual traffic capacity are conducted separately corresponding to repair orders, and the significant impacts to total seismic loss caused by difference of capacity level are revealed. Therefore, the identification study for appropriate residual traffic capacity needs to be performed in the future. As practical utilization, the detailed assessments for simulated restoration process and total loss are demonstrated for effective usage of this developed methodology to make a decision in terms of damage mitigation and resilience enhancement.

As summarized above, the established innovative transportation network model considering repair prioritization and practical reconstruction progress can simulate various restoration processes and relating economic losses over time such as system resilience corresponding to repair orders. It can examine considerable difference of recovery progress and total seismic loss between each repair orders, and it is necessity to explore better repair orders based on several priorities involving stakeholders' benefits. The estimation of thinkable disaster scenario and conceivable post-earthquake process contributes for planning policy and making decision for damage mitigation. Additionally, the basic scheme including several original algorithms can be employed to recovery assessment of other infrastructure network systems such as electric power, water distribution and telecommunication, and it can be applied to other disaster risk estimation like hurricane, flood, tsunami, and so on.

6.2 Future works

Although a practicable method to simulate post-earthquake process based on multidisciplinary fields is built here, it is necessary to implement further studies for enhancing accuracy of simulation and usability of this model to aid decision-making. Both physical factors (e.g., highway structural components) and functional factors (e.g., network system interdependency) of the model should be considered for this purpose. For instance, several topics need to be coped as future studies as follows:

(1) Expansion of model configuration in terms of vulnerable highway components should be considered, which means that seismic strength of tunnel, roadway, retaining wall, embankment and cut-off slope ought to be combined with bridge seismic fragility.

(2) More consideration and quantification of uncertainties associated with dominant factors of the model such as bridge damage identification, prioritization criteria weight, available regional labor, Markov transition probability and residual link capacity have to be studied.

(3) Development of disaster risk assessment model considering the total loss during restoration process should be done for estimating regional risk on the basis of all possible future disasters for preparedness of damage mitigation and system resilience enhancement.

(4) An integrated model of several infrastructure network systems considering the interdependency between highway network and other infrastructure systems has to be established for simulating a post-earthquake cascading reaction of an entire society.

(5) Regional seismic hazard such as regional potential scenario earthquakes in this study needs to be updated periodically from the standpoint of probabilistic estimation, and emerging possible earthquakes have to be studied and be added to the model.

(6) Analysis algorithms depending on actual data such as prioritizing criteria, necessary construction labor, regional limited labor, residual traffic capacity and bridge fragility should be continuously enhanced by investigating actual recorded data.

As well as advancing the above tasks, the construction of a system for collecting every piece of information concerning damage restoration process at future disasters is very important and is useful to improve this developed simulation framework and to establish beneficial database like Big Data.

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