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U.S. Department of Transportation
Federal Highway Administration

REDARS 2 Methodology and Software for Seismic Risk Analysis of Highway Systems

By
Stuart D. Werner, Craig E. Taylor, Sungbin Cho, Jean-Paul Lavoie, Charles Huyck, Chip Eitzel, Howard Chung and Ronald T. Eguchi

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MCEER

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MCEER is a national center of excellence dedicated to establishing disaster-resilient communities through the application of multidisciplinary, multi-hazard research. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation (NSF) in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission has expanded from its original focus on earthquake engineering to address a variety of other hazards, both natural and man-made, and their impact on critical infrastructure and facilities. The Center's goal is to reduce losses through research and the application of advanced technologies that improve engineering, pre-event planning and post-event recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

Funded principally by NSF, the State of New York and the Federal Highway Administration (FHWA), the Center derives additional support from the Department of Homeland Security (DHS)/Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

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EXECUTIVE SUMMARY

Earthquake damage to components in a highway system (e.g., bridges, tunnels, roadways, etc.) can cause major traffic disruption which, in turn, can adversely impact the region's economic recovery and emergency response. These impacts will depend not only on the seismic performance of the components in the system, but also on the properties of the system itself such as its network configuration and roadway characteristics (e.g., locations, redundancies, and traffic-carrying capacities). Unfortunately, such traffic impacts are usually not considered in seismic risk reduction activities at state transportation agencies. One reason for this has been the lack of a technically-sound and practical method for estimating these impacts.

To address this deficiency, a new methodology for seismic risk analysis (SRA) of highway systems nationwide has been developed as part of the two six-year seismic research projects that have been carried out at MCEER under the sponsorship of the Federal Highway Administration. During the first project, the methodology was initially developed and demonstrated in an application to the highway system in Shelby County, Tennessee. Under the second (current) multi-year project, the methodology was validated, its models were updated, and it was programmed into a public-domain software package named REDARS™ 2 (Risks from Earthquake DAmage to Roadway Systems). A demonstration application of the software to the Los Angeles, California highway system was also conducted.

For any given earthquake, REDARS™ 2 uses state-of-knowledge models to estimate: (a) seismic hazards (ground motions, liquefaction, and surface fault rupture) throughout the highway system; (b) the resulting damage states for each component in the system; and (c) how each component's damage will be repaired, including its repair costs, downtimes, and time-dependent traffic states (i.e., its ability to carry traffic as the repairs proceed over time after the earthquake). Next, REDARS™ 2 includes these traffic states into a highway-network link-node model, in order to form a set of system-states that reflect the extent and spatial distribution of link closures at various times after the earthquake. Then, REDARS™ 2 applies network analysis procedures to each system-state, in order to estimate how these closures affect system-wide travel times and traffic flows. Finally, REDARS™ 2 estimates corresponding economic losses and increases in travel times to/from key locations or along key lifeline routes. These steps can be applied for single earthquakes and no uncertainties (deterministic analysis), or for multiple earthquakes and simulations in which uncertainties in earthquake occurrence and in estimates of seismic hazards and component damage are considered (probabilistic analysis).

REDARS™ 2 can serve as a pre- or post-earthquake decision-guidance tool. As a pre-earthquake planning tool, it can be used to: (a) estimate the effectiveness of various seismic-upgrade options in reducing earthquake losses; (b) compare costs and benefits (e.g., reduction in traffic-related losses/risks) for each option; and (c) enable decision-makers to use these results in order to make a more informed selection of a preferred option to implement. As a post-earthquake emergency-response tool in real time, REDARS™ 2 can incorporate actual damage data from the field, and can then develop results to enable officials to assess the relative abilities of various repair options and traffic-management options to facilitate traffic flows.

This report contains eight chapters and eleven appendices, whose contents are summarized below:

Chapter 1. Introduction. Chapter 1 includes a statement of the problem addressed by this research, and a discussion of the research benefits and the anticipated users of the research.

Chapter 2. Seismic Risk Analysis Methodology. Chapter 2 describes the main features of the REDARS™ 2 SRA methodology, including its analysis modules and procedures, and how its results can be used to guide seismic-improvement decision making. Appendix A describes the REDARS™ 2 probabilistic framework, and Appendix C summarizes a REDARS™ 2 Import Wizard that was developed under this research program to greatly simplify the development of input data for a SRA application. Appendix J describes a new statistical-analysis procedure that was developed under this project to estimate confidence limits in probabilistic SRA results.

Chapter 3. Earthquake Modeling and Hazards Module. Chapter 3 summarizes: (a) the "walkthrough" process that is used in REDARS™ 2 for probabilistic SRA applications; (b) the development of scenario-earthquake walkthrough tables for this process; and (c) the models that are currently used in REDARS™ 2 to estimate ground-motion, liquefaction, and surface-fault-rupture hazards. Appendix B describes the development of earthquake walkthrough tables for coastal California and the central United States under this project, and Appendices D, E, and F further describe the above ground-motion, liquefaction, and surface-fault-rupture hazard models.

Chapter 4. Component Module. Chapter 4 describes how REDARS™ 2 uses either default or user-specified models to estimate component damage and repair requirements, and how such models are developed for deterministic and probabilistic SRA applications. In addition, the chapter summarizes the default models that are now included in REDARS™ 2 to estimate damage states and repair requirements for bridges, approach fills, roadways, and tunnels. Appendices G and H provide further detail on the default modeling methods for these component types, and Appendix K describes how the model for estimating bridge damage due to ground shaking was calibrated against Northridge Earthquake bridge-damage observations.

Chapter 5. Transportation Network Analysis. Chapter 5 summarizes the features of the REDARS™ 2 transportation network analysis procedure, including its variable-demand model, its minimum-path algorithm for reducing run times, and its approach for considering multiple trip types. Appendix I provides further details on this network analysis procedure.

Chapter 6. Economic Module. Chapter 6 describes the approach used in REDARS™ 2 to develop default estimates of economic losses due to repair costs, travel-time delays, and trips foregone, and how user-specified parameters can be used to override these default estimates.

Chapter 7. Demonstration Application. Chapter 7 describes a demonstration application of the REDARS™ 2 software to carry out deterministic and probabilistic SRA of a large segment of the Los Angeles highway-roadway system. The chapter also includes a "hindsight" probabilistic economic analysis of a prior bridge retrofit program within this system, in order to illustrate one way that REDARS™ 2 results can be used to guide seismic-risk-reduction decision making.

Chapter 8. Conclusion. Chapter 8 contains concluding comments and recommended directions for continued development and application of the REDARS™ 2 methodology and software

ACKNOWLEDGEMENTS

This REDARS™ 2 technical manual describes seismic risk analysis (SRA) research performed under Tasks B1-2 and B1-4 of the project titled "Seismic Vulnerability of the Highway System." This project was directed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) under Federal Highway Administration (FHWA) sponsorship.

This SRA research was performed by a REDARS™ Development Team comprised of Stuart D. Werner (earthquake engineering, and principal investigator for development of REDARS™ 2 and for Task B1-2), Craig E. Taylor of Natural Hazards Management Inc. (risk analysis, earthquake modeling, and hazard modeling), Sungbin Cho of ImageCat Inc. (network analysis, Import Wizard development, and seismic modeling and analysis support), Jean Paul Lavoie of Geodesy (lead programmer for REDARS™ 2 SRA software, with support from his co-worker at Geodesy, Chip Eitzel), Charles Huyck of ImageCat Inc. (Import Wizard development and programming support), Howard Chung of ImageCat Inc. (seismic modeling and analysis support), and Ronald T. Eguchi of ImageCat Inc. (principal investigator for Task B1-4 and internal project review). In addition, the following major contributors are acknowledged:

- Dr. Ian Buckle, Dr. George Lee and Mr. Jerry O'Connor for their leadership of this overall FHWA-MCEER research project on behalf of MCEER, and their encouragement and helpful suggestions throughout this research.
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Over the past 2½ years, the California Department of Transportation (Caltrans) has also supported this work through a "REDARS Demonstration Project." The objective of this project has been to assess the applicability of the REDARS™ SRA methodology and software to Caltrans' seismic risk reduction programs. During the course of this project, their staff beta tested the REDARS™ 2 software, facilitated the development of the default component repair models presented in this manual that were largely based on the experience and background of their technical staff, and provided helpful suggestions throughout the project. The support of the following Caltrans project staff is particularly acknowledged: Mandy Chu (Caltrans' project manager); Zhongren Wang, Brian Chiou, Loren Turner, and Mike Jenkinson (beta testers and technical reviewers); and the following members of their technical staff who interacted with REDARS Development Team members during this project: Dan Adams, Randy Anderson, Matt Bailey, Bill Farnback, Minh Ha, Tom Harrington, Leo Mahserelli, Ray Mailhot, Tinu Mishra, Ganapathy Murugesh, Steve Sahs, Tom Shantz, Kirsten Stahl, Kevin Thompson, Brian Weber, Mark Yashinsky, and Foued Zayati.

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****NOTE: Appendices A – K are provided in PDF format on the CD affixed to the back cover of this report.**

LIST OF ACRONYMS

AAL	Average Annualized Loss
AC	Asphalt Concrete
ADOX	Active Data Object Extension
CALTRANS	California Department of Transportation
CERI	Center for Earthquake Research and Information
CGS	California Geological Survey
CI	Confidence Interval
CUS	Central United States
ER&R	Earthquake Response and Recovery
FDM	Fixed-Demand Model
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GIS	Geographic Information Systems
GUI	Graphical User Interface
HPMS	Highway Performance Monitoring System
LA	Los Angeles
LRS	Linear Referencing System
MDB	Microsoft Access Database
MPO	Metropolitan Planning Organization
NBI	National Bridge Inventory
NCEDC	Northern California Earthquake Data Center
NEHRP	National Earthquake Hazards Reduction Program
NHPN	National Highway Planning Network
OD	Origin-Destination
PGA	Peak Ground Acceleration
PGD	Permanent Ground Displacement
PSHA	Probabilistic Seismic Hazard Analysis
RCR	Repair Cost Ratio
RDF	REDARS Data File
REDARS	Risk from Earthquake Damage to Roadway Systems

RPR	REDARS Probabilistic Analysis
RVB	REDARS Visual Basic for Application
SCAG	Southern California Area of Governments
SCEC	Southern California Earthquake Center
SRA	Seismic Risk Analysis
TAZ	Traffic Analysis Zone
TCW	Tri-Center Workshops
USGS	United Stated Geological Survey
VDM	Variable-Demand Model
ZOD	Zone of Deformation

CHAPTER 1: INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Past experience has shown that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can go well beyond life safety risks and the costs to repair the component itself. Rather, such damage can also severely disrupt traffic flows and this, in turn, can impact the economy of the region as well as post-earthquake emergency response, repair, and reconstruction operations. Furthermore, the extent of these impacts depends not only on the seismic performance characteristics of the individual components, but also on the characteristics of the highway system that contains these components. System characteristics that will affect post-earthquake traffic flows include: (a) the highway system network configuration; (b) locations, redundancies, and traffic capacities and volumes of the system's roadway links; and (c) component locations within these links (Basoz and Kiremidjian, 1996; Shinozuka et al., 1999, Wakabashi 1999; Werner et al., 2004).

From this, it is evident that earthquake damage to certain components (e.g., those along important and non-redundant links within the system) will have a greater impact on the system performance (e.g., post-earthquake traffic flows) than will other components. Unfortunately, such system issues are typically ignored when specifying seismic retrofit priorities, performance requirements, and design/strengthening criteria for new and existing components; i.e., each component is usually treated as an individual entity only, without regard to how the extent of its damage from earthquakes may impact highway system performance. For example, current criteria for prioritizing bridges for seismic retrofit represent the importance of the bridge as a traffic-carrying entity only by using average daily traffic count, detour length, and route type as parameters in the prioritization process. These criteria do not account for the systemic effects associated with the loss of a given bridge, or for combinatorial effects associated with the loss of other bridges in the highway system. However, consideration of these systemic and combinatorial effects can provide a much more rational basis for establishing seismic retrofit priorities and performance requirements for bridges and other highway components.

1.2 PRIOR FHWA-MCEER DEVELOPMENT EFFORTS

During the period extending from 1993-2000, the Federal Highway Administration (FHWA) sponsored a seismic research project that was directed and conducted by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The purpose of this program was to develop: (a) seismic retrofit and evaluation methodologies for existing highway systems and structures (including bridges and also tunnels, retaining structures, slopes, culverts, and pavements); and (b) improved seismic design criteria and procedures for these structures.

One of the tasks from this project was to develop a new methodology for seismic risk analysis (SRA) of highway systems that addresses the issues summarized in Section 1.1. This methodology is named REDARS™ (Risks from Earthquake DAmage to Roadway Systems). It uses data and models from the geosciences (seismology and geology), engineering (structural, geotechnical, and transportation), repair and reconstruction, system evaluation (for roadway transportation network analysis), and economics, in order to develop deterministic and probabilistic estimates of the seismic performance of highway systems. In this, seismic performance of these systems is measured in terms of potential for earthquake-induced disruptions of system-wide travel times and traffic flows, and the economic impacts and other losses due to these disruptions. The methodology was successfully used to estimate seismic risks and potential earthquake-induced losses to the highway in Shelby County, Tennessee (Werner et al., 2000).

1.3 CURRENT PROJECT

After the above research was completed, a second multi-year FHWA-MCEER seismic research project has been carried out to perform various structural, geotechnical, and SRA tasks that focused on the seismic performance of the highway system. This report is a one of the final deliverables that is the combined effort of two of these tasks -- Tasks B1-2 and B1-4. These tasks focused on validation of the REDARS™ methodology that was developed under the prior FHWA-MCEER project, updating of the REDARS™ modules and models from the prior project, and development of the REDARS™ methodology into a public-domain software package that can be used to assess the seismic performance of highway systems nationwide.

This task resulted in the development of two software packages -- REDARS™ 1, which was interim demonstration software and REDARS™ 2 which is the end product of this public-domain software development effort. REDARS™ 1 performs simplified deterministic SRA of the Los Angeles area highway system for which SHAKEMAP ground-motion data are available (http://earthquake.usgs.gov/shakemap). Development of this interim software was motivated by the interest of several state highway transportation agencies, and the need to: (a) provide a simple tool to familiarize these agencies with basic SRA concepts, while the more extensive public-domain software REDARS™ 2 was being developed; and (b) enable the agencies to provide early feedback regarding desirable features to include in REDARS™ 2 (Werner et al., 2003).

Development of the REDARS™ 2 software package is now complete. This report describes the various models and modules that are included in this software, together with results of a demonstration application of the software to the northern Los Angeles area highway system. It is intended to familiarize users of REDARS™ 2 with the technical features of the software, and how it can be used to guide decision makers from government, transportation agencies, and consulting firms in their establishment of rational pre-earthquake risk-reduction strategies and post-earthquake risk reduction measures. In this, the unique feature of REDARS™ 2 is its ability to include traffic flow and travel time impacts in the assessment of alternative strategies that may be under consideration.

1.4 BENEFITS

This section summarizes the main benefits of REDARS™ 2 in terms of its capabilities to: (a) perform multiple levels and types of SRA applications that will accommodate the needs of a wide variety of users; and (b) serve as a pre- and post-earthquake decision guidance tool.

1.4.1 APPLICATIONS

REDARS™ 2 can implement a wide variety of deterministic and probabilistic analyses that will facilitate its application as a tool for pre-earthquake planning and for post-earthquake emergency response. It was specifically developed for use in the following types of applications by transportation agencies and/or their consultants:

- ***Pre-Earthquake Planning***. REDARS™ 2 can be used to evaluate and assess alternative pre-earthquake planning strategies and priorities for strengthening of existing highway components, establishing appropriate design criteria for new highway components, expanding the highway system, etc.

- ***Post-Earthquake Emergency Response.*** REDARS™ 2 can be used in real time after an actual earthquake to assist with emergency response activities in areas where SHAKEMAP-type ground-motion data have been recorded and transmitted back to a regional response-coordination center. For example, immediately after an earthquake (and before field inspectors have identified actual damage), REDARS™ 2 may be used to estimate potential "hot spots" within the highway system that may be likely to experience earthquake damage. In addition, after actual damage data for bridges and other components are obtained from field surveys, REDARS™ 2 can carry out analyses that incorporate these field damage data in order to: (a) estimate potential earthquake-damage consequences for the highway system (e.g., traffic flow bottlenecks, difficulties in accessing key medical or other emergency response facilities, etc.); and (b) help to assess various emergency response strategies for reducing these consequences (e.g., which damaged bridges to repair first, traffic rerouting around damaged areas, etc.).

1.4.2 DECISION GUIDANCE TOOL

The REDARS™ 2 SRA methodology can be applied to the existing system as well as to modified systems in which various seismic-risk-reduction options are modeled. In this way, the SRA methodology can indicate the effectiveness of these options in reducing system-wide economic and traffic flow impacts of system damage due to earthquakes. For example, options associated with each of the following types of seismic risk reduction can be evaluated:

- ***How should the System be Improved?*** The SRA methodology can evaluate relative effects of various system enhancement options for improving post-earthquake seismic performance. System enhancements that could be evaluated include: (a) strengthening of individual components; (b) construction of additional roadways to expand system redundancy; and (c) alternative post-earthquake traffic-management strategies.

- ***What Components should be Retrofitted First?*** REDARS™ 2 can be used when establishing priorities for retrofit of bridges and other roadway components, by enabling users to consider how various prioritization options could impact post-earthquake system performance. This can be accomplished by using the methodology to assess the how much the seismic performance of the overall highway system (i.e., how losses due to system-wide travel time delays) are improved when different sequences of component retrofits are followed.

- ***How should the Components be Retrofitted?*** The SRA methodology can also evaluate alternative retrofit strategies for the individual components and their relative impacts on post-earthquake traffic flows, travel times, and trip demands. For example, for those components selected for retrofit, SRA can assess the relative effectiveness of alternative levels and types of seismic strengthening in reducing system-wide traffic disruptions and economic losses, as well as overall repair costs. When assessing these options, these relative benefits should be weighed against the relative cost of each level and type of retrofit.

- ***What Post-Earthquake Response and Recovery (ER&R) Strategies should be Carried Out?*** Results from the SRA methodology can guide the planning of ER&R strategies that would be most effective in the presence of actual damage to the highway system. Such results can also guide the prioritization of highway-system risk-reduction options that would optimize the effectiveness of ER&R operations after an earthquake.

- ***How can Traffic best be Managed after an Earthquake?*** The effectiveness of various post-earthquake traffic-management strategies for reducing congestion can be tested by applying the SRA methodology.

- ***What Funding Level is Appropriate for Improving the System's Seismic Performance?*** Because SRA can estimate economic impacts of highway-system damage, it can help to justify government funding levels for system-wide seismic strengthening programs.

Section 2.5 of Chapter 2 provides further discussion of how the REDARS™ 2 SRA methodology can guide seismic risk reduction decision making.

1.5 USERS

REDARS™ 2 can be used by decision makers, technical staff, and researchers, as described below.

Decision makers are senior members of a transportation-agency staff, who have the ultimate responsibility and authority for: (a) identifying options for pre-earthquake seismic-risk-reduction or post-earthquake emergency response that are to be considered for the highway system; and for (b) selecting a preferred option that best meets highway-system-user needs and agency cost and acceptable-risk constraints. It is anticipated that these decision makers would direct technical staff, who would carry out the actual running and implementation of the REDARS™ 2 SRA for each option and then provide the analysis results to the decision maker for his/her review. To facilitate use of REDARS™ 2 by such decision makers, the software has been designed to provide a variety of deterministic and probabilistic output in clear and concise tabular, graphical, and GIS formats.

Technical staff consists of those users of REDARS™ 2 with the technical background for developing the appropriate input data, understanding the various models and modules that are included in REDARS™ 2, overriding REDARS™ 2 default models/data with user-specified models/data where appropriate, running the software, and interpreting its results.

Since the REDARS™ 2 SRA methodology is multidisciplinary, it is anticipated that, for a given application, the above tasks could be carried out by a team of multiple technical staff members (rather than a single staff member) who together encompass the range of engineering and scientific disciplines embodied in REDARS™ 2. It is further anticipated that this technical staff would work closely with the decision makers to support their planning of the SRA cases and options to be considered and their interpretation of the analysis results.

Researchers are representatives of university staffs or consulting firms who are experts in one or more of the technical disciplines embodied in the REDARS™ 2 methodology. Accordingly, they may use REDARS™ 2 in various research and development applications. For example, such applications could include improvement of REDARS™ 2 models/modules, investigation of consequences of various seismic-improvement or emergency-response options that may be considered for a particular scenario, and identification/evaluation of other types of output and results that may be developed by REDARS™ 2.

1.6 REPORT OUTLINE

The remainder of this report is organized into eight main chapters and eleven appendices. The eight chapters provide the basic framework and a demonstration application of the SRA methodology and its modules. Chapter 2 provides a summary of the main elements of the REDARS™ 2 SRA methodology. Chapters 3 through 6 summarize the main elements of the hazards, component, system, and economic modules of the methodology. A demonstration application of the SRA methodology to the northern Los Angeles, California highway system is provided in Chapter 7. Chapter 8 provides concluding comments and recommended directions for future maintenance, support, and upgrading of the REDARS™ 2 SRA methodology and software.

The eleven appendices of this report provide additional technical detail on the material contained in the main chapters. In particular, they address the probabilistic framework for the REDARS™ 2 SRA methodology (Appendix A), development of the earthquake walkthrough tables now included in REDARS™ 2 (Appendix B), the REDARS™ 2 Import Wizard which has been programmed to automate development of much of the input data needed for SRA of an actual highway system (Appendix C), the seismic hazard models for estimating seismic hazards from ground shaking, liquefaction, and surface fault rupture that are now built into REDARS™ 2 (Appendices D through F), the default procedures used to estimate damage states and repair costs, downtimes, and traffic states for bridges, approach fills, pavements, and tunnels (Appendices G and H), the network analysis procedure (Appendix I), a variance reduction procedure that has been developed under this project to assess confidence levels and limits in probabilistic loss results as increasing numbers of simulations are included (Appendix J), and advanced statistical analysis procedures for modifying the original default bridge model to enable its damage-state predictions for the Northridge earthquake to be more consistent with earthquake damage observations (Appendix K).

CHAPTER 2: SEISMIC RISK ANALYSIS METHODOLOGY

2.1 OVERVIEW

REDARS™ 2 enables users to carry out deterministic or probabilistic SRA for any user-specified highway system within the United States. The methodology for accomplishing this is shown in Figure 2-1. For probabilistic SRA, results are developed for multiple simulations, in which a "simulation" is defined as a complete set of system SRA results for one particular set of randomly selected input parameters and model parameters. The model and input parameters for one simulation may differ from those for other simulations because of random and systematic uncertainties. For deterministic SRA, one set of results is developed either for median input and model parameters or for one set of randomly-selected parameters.

For each simulation of a probabilistic SRA or for the single set of input parameters for a deterministic SRA, this multidisciplinary procedure uses geoseismic, geotechnical and structural engineering, repair/construction, transportation network, and economic models to estimate:

- ***Hazards.*** Seismic hazards at the site of each component in the highway system.

- ***Component Performance.*** Each component's damage state and traffic state due to these site-specific seismic hazards, in which the traffic state reflects the component's ability to carry traffic at various times after the earthquake as the damage is being repaired.

- ***System Performance.*** System-wide traffic flows (e.g., travel times, paths, and distances) throughout the system, also at various times after the earthquake, that are dependent on each component's traffic state, the redundancies and traffic-carrying capacities of the various roadways that comprise the system, and the trip demands (i.e., the number, type, origin, and destination for all trips that use the highway system).

- ***Losses.*** Consequences of earthquake-induced damage to the highway system, including: (a) economic impacts (repair costs and losses due to travel time delays); increases in travel times to/from key locations in the region (e.g., medical facilities, airports, centers of commerce, etc.); and (c) increases in travel times along "lifeline" routes within the system, which are previously designated routes that are essential for emergency response or national defense.

2.2 FEATURES

This REDARS™ 2 SRA methodology has the following features.

- ***Modular.*** The methodology includes a series of seismic-analysis modules (Fig. 2-2) that contain the input data and analytical models needed to characterize the highway system and its seismic performance, the seismic hazards, the seismic performance of the components, and the economic losses due to repair costs and traffic disruption. This modular structure will facilitate the inclusion of improved REDARS™ hazards, component, and network models, as they are developed from future research. It is further described in Section 2.3.

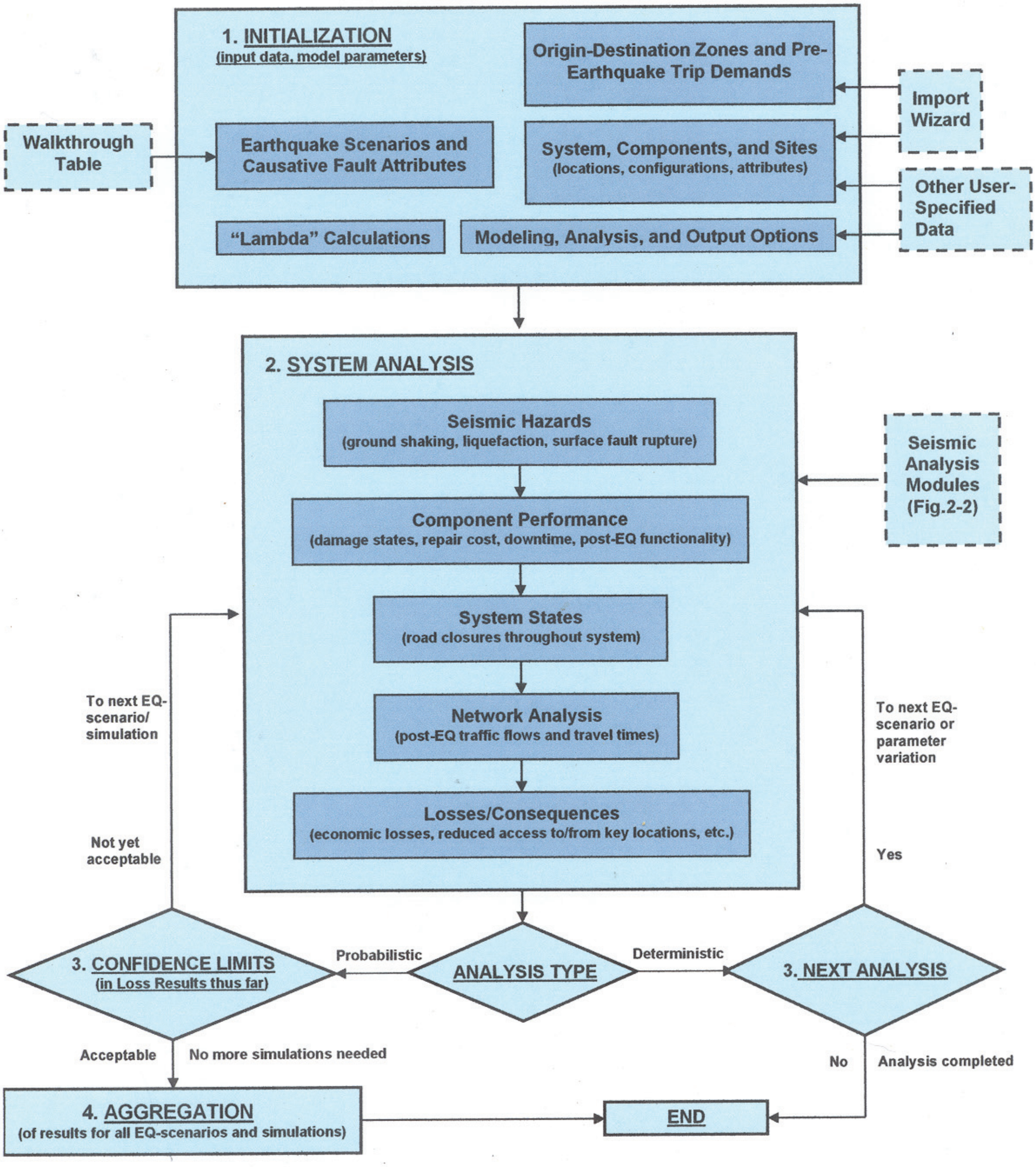

Figure 2-1. REDARS™ 2 Methodology for Seismic Risk Analysis of Highway Systems

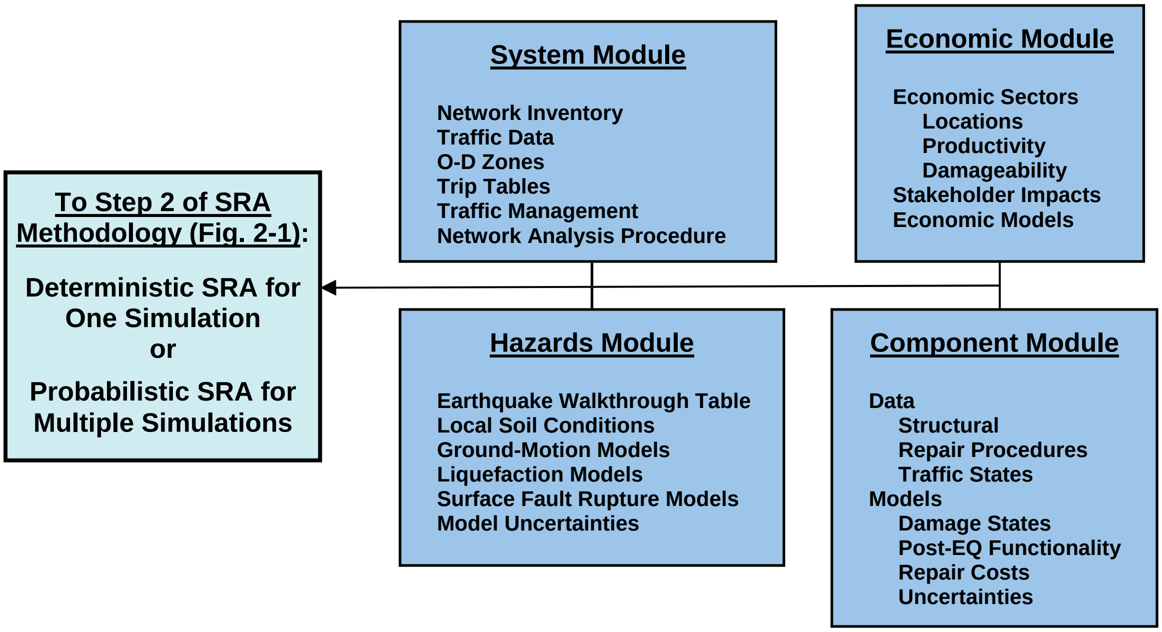

Figure 2-2. REDARS™ 2 Seismic Analysis Modules

- ***Multidisciplinary.*** The SRA methodology is a synthesis of models developed by earth scientists, geotechnical and structural earthquake engineers, transportation engineers and planners, and economists.

- ***Wide Range of Results.*** The methodology can develop multiple types/forms of results from deterministic or probabilistic SRA, in order to meet needs of a wide range of possible future users. Such results can be developed for use in pre-earthquake assessment of various options for seismic risk reduction, in which the effectiveness of each option in reducing losses due to highway-system disruption is evaluated. Results can also be developed for use in real time after an actual earthquake, in order to enable responders to assess the effectiveness of various options for reducing traffic congestion after an actual earthquake.

- ***Confidence Intervals (or Confidence Limits) for Probabilistic Loss Results.*** As loss results are developed from each multiple simulation in a probabilistic SRA, running displays of confidence intervals (CIs) in the loss results are displayed. Since the CIs improve as additional simulations are considered, these CI displays enable users to assess whether a sufficient number of simulations have been considered and the analysis can be terminated. This feature can substantially reduce analysis times for probabilistic SRA applications.

- ***Import Wizard.*** To carry out SRA of highway systems, publicly available databases must be used to define: (a) roadway topology and attributes; (b) bridge locations and attributes; (c) origin-destination (O-D) zones and pre-earthquake trip tables; and (d) site-specific NEHRP soil conditions (Figure 2-3). However, experience has shown that use of these databases can be time consuming due to various data inconsistency, connectivity, and continuity issues that often arise. Therefore, REDARS™ 2 includes an "Import Wizard" that facilitates the use of these publicly available databases by: (a) accessing the publicly available databases; (b) guiding the user though the application of these databases to develop input data for REDARS™ 2; (c) resolving any inconsistencies between data from the various databases; and (d) checking the resulting highway-network model and the connectivity and continuity of the O-D zones. The Wizard is further described in Appendix C of this Manual and in Cho et al. (2006b).

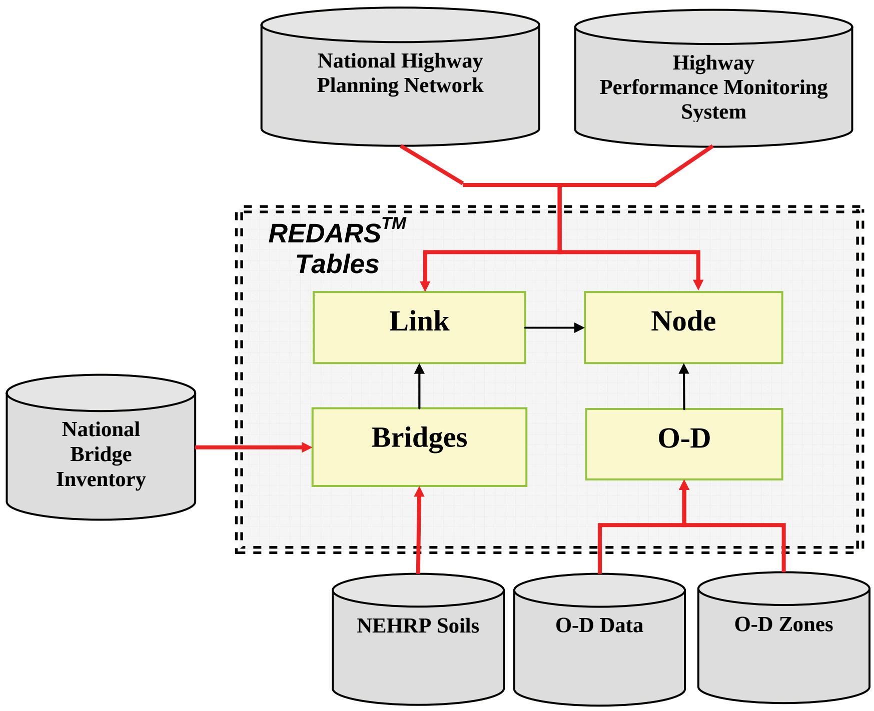

Figure 2-3. Development of REDARS™ 2 Input Data from Publicly Available Databases

2.3 SEISMIC ANALYSIS MODULES

The four REDARS™ 2 seismic analysis modules that are shown in Figure 2-2 are described in the following paragraphs.

2.3.1 SYSTEM MODULE

The system module contains input data and models for characterizing the highway system and its seismic performance (traffic flows, travel times, etc.) at various times after an earthquake.

2.3.1.1 Input Data

The input data contained in the System Module includes: (a) system network configuration linkages, and component types and locations; (b) numbers of lanes, traffic flows, capacities, and congestion functions for each highway link; (c) origin-destination (O-D) zones, the various trip types to be considered in the SRA (i.e., auto various types of freight, etc.) and, for each trip type, the pre-earthquake trip tables; (d) any in-place traffic-management measures for modifying the system to ease post-earthquake traffic congestion (e.g., detour routes, changing roadways from two-way to one-way traffic, etc.); and (e) any special system characteristics, such as certain highways being critical for emergency response or national defense.

In order to develop the above data listed under Items (a), (b), and (c) above, the REDARS™ 2 user must first contact the Metropolitan Planning Organization (MPO) for the region being investigated, in order to obtain data that define the region's O-D zones and its trip tables for the various types of trips that are to be considered. Then, these O-D data are input into the Import Wizard, which also accesses various federal databases (i.e., the National Highway Planning Network, Highway Performance Monitoring System, and National Bridge Inventory databases, as shown in Figure 2-3) and then processes all of these data in order to provide them in a form that can be directly input into the REDARS™ 2 SRA.

The input data that describe post-earthquake traffic-management measures and special system characteristics (Items (d) and (e) above), are obtained by contacting the state, county, or local transportation departments for the region being evaluated.

2.3.1.2 Transportation Network Analysis Procedure

The transportation network analysis procedure contained in the System Module estimates post-earthquake traffic flows throughout the highway system, for each simulation and scenario earthquake. The procedure has the following features: (a) it represents the latest well-developed technology for providing rapid and dependable estimates of flows in congested networks, for given changes in network configuration due to earthquake damage; (b) it includes a "variable demand" feature that accounts for reductions in trip demands that would occur due to increased traffic congestion after an earthquake; (c) it accommodates various types of trips along the highway system (i.e., via automobile, via trucking for various types of freight, etc.) by enabling the user to specify separate trip tables for each trip type; and (d) it uses a numerically efficient minimum-path algorithm to significantly reduce computer times for estimating post-earthquake traffic flows. This procedure is further described in Chapter 5, and Appendix I of this report.

2.3.2 HAZARDS MODULE

The Hazards Module contains input data and models for characterizing system-wide seismic hazards for each scenario earthquake and simulation considered in the SRA of the highway system. The seismic hazards evaluated in the current Hazards Module are ground motion, liquefaction, and surface fault rupture. Earthquake-induced landslide hazards are not included at this time, but will be added into the next version of REDARS™.

2.3.2.1 Input Data

Input data used in the Hazards Module to evaluate seismic hazards for a probabilistic SRA consist of: (a) multiple earthquake scenarios, provided as a "walkthrough table" that specifies earthquake occurrences (magnitudes and locations) over time in accordance with established earthquake models for the region (see Section 2.4.1 and Appendix B); (b) local soil conditions throughout the system, for use in estimating local geologic effects on ground shaking and the potential for liquefaction; and (c) locations and characteristics of any faults within the system that can produce surface rupture. Charter 3 provides a further description of these input data.

Deterministic SRA in REDARS™ 2 can be based on one of the following options: (a) a single earthquake from the walkthrough table, or any other earthquake with a user-specified magnitude and location; or (b) ShakeMap input data, which consist of near real-time maps of ground motion and shaking intensity following significant earthquakes (http://earthquake.usgs.gov/shakemap)[1]. For the first option, the input data are identical to that described above for probabilistic SRA applications, except that a single earthquake is considered instead of a walkthrough table of multiple earthquake scenarios. For ShakeMap applications, REDARS™ 2 downloads ground-motion maps directly from the above website.

2.3.2.2 Hazards Estimation Models

The main features of the hazards models currently included in REDARS™ 2 are summarized below, and are further described in Chapter 3 and Appendices D, E, and F of this report.

2.3.2.2(a) Ground-Motion Hazards

For each scenario earthquake and simulation, ground-motion hazards for a given scenario earthquake are estimated at the site of each component in the highway system. In most applications, these estimates are developed from ground-motion models built into REDARS™ 2 that consider: (a) site-specific rock motions, and their rate of attenuation over the distance from the seismic source to the site; (b) effects of local soil conditions in modifying the ground surface motions in the vicinity of the bridge or other highway component, relative to the underlying rock motions; (c) effects of faulting/directivity; and (d) uncertainties in these various estimates (if probabilistic SRA is being carried out. These ground-motion hazards are provided as peak accelerations or spectral accelerations at various natural periods, depending on the requirements of the component damage-state model[2].

2.3.2.2(b) Liquefaction Hazards

When the ground-motion hazards are estimated at each potentially liquefiable site in the highway system, liquefaction hazards are then estimated. In this, the potentially liquefiable sites within the system must be identified beforehand by the REDARS™ 2 user, through an initial geologic screening that is based on the REDARS™ 2 user's review of site soil conditions and topography. Then, for each potentially liquefiable site, permanent ground displacement (PGD) hazards (lateral spreading and vertical settlement) are evaluated for each scenario earthquake, using

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[1] ShakeMap is a product of the United States Geologic Survey's Earthquake Hazards Program in conjunction with seismic network operators. At this time (June 2006), ShakeMap real-time ground motion maps can be generated in Northern California, Southern California, the Pacific Northwest, Nevada, Utah, and Alaska. In addition, ShakeMap estimates of ground motions from various hypothetical earthquakes or prior actual earthquakes are available.

[2] Of course, if deterministic SRA using a ShakeMap ground-motion map is instead being carried out, site-specific ground-motion hazards are estimated directly from these maps.

models that account for effects of uncertainties and the site's subsurface soil conditions, water table depth, ground shaking due to that earthquake, and topography.

2.3.2.2(c) Surface Fault Rupture Hazards

For each scenario earthquake that is caused by rupture along a fault of finite length that extends up to or very near the ground surface, PGD hazards are estimated at those sites within the highway system that fall in the fault rupture's zone of deformation. These estimates use input data that define the fault rupture attributes (location, orientation, type, rupture plane dip and directions) and the earthquakes magnitude and location within the rupture plane. From this, each component near the fault rupture is assessed to estimate whether it actually falls with the rupture's zone of deformation. For sites within this zone, PGDs are then estimated. Effects of uncertainties are included in these various estimates.

2.3.3 COMPONENT MODULE

2.3.3.1 Overview

The Component Module contains input data and models for estimating: (a) each component's seismic response to site-specific ground shaking and PGD hazards that are estimated by the models in the Hazards Module; (b) the component's "damage state," (i.e., the degree, types, and locations of any earthquake damage to the component); (c) how the damage will be repaired; (d) the costs and time duration of these repairs; and (e) the component's "traffic state" (i.e., whether it will need to be fully or partially closed to traffic during the repairs, and the durations of these closures). These traffic states will vary with time after the earthquake, to reflect the rate of traffic restoration over time as the repairs proceed.

2.3.3.2 Default and User-Specified Models

REDARS™ 2 contains first-order default models for estimating earthquake-induced damage states and associated repair requirements for bridges, pavements, and approach fills. The end results of these estimates are component repair costs and time-dependent traffic states, as a function of the level of site-specific ground motion and PGD. For bridges, these default models are probabilistic (in the form of fragility curves) whereas, for pavements and approach fills, they provide deterministic estimates of repair costs and traffic states as a function of PGD only. The models are further described in Chapter 4 and Appendices G and H of this report.

REDARS™ 2 also enables users to override any component's default model with a user-specified model. For bridges or tunnels, these user-specified models are typically based on detailed seismic analyses that are carried out by the user prior to the start of the REDARS™ 2 SRA. They take the form of fragility curves that prescribe the probability of occurrence of various damage states (and associated repair costs and traffic states) as a function of the level of ground shaking and PGD. For pavements and approach fills, the user-specified models consist of modifications to the default models. For tunnels, REDARS™ 2 requires that user-specified models must always be provided, in view of the variations in structural and site conditions and that will virtually always be present between various tunnels.

User-specified models for bridges will provide more refined seismic-performance estimates than will the default models. Therefore, they are most appropriate for modeling of bridges that: (a) have unique geometries and/or structural attributes; (b) are located along routes that are either non-redundant or are critical to post-earthquake response; or (c) will have a large impact on traffic flows over a significant portion of the highway system, if they are severely damaged. For example, in a past application of an early version of REDARS™ to the Shelby County (Memphis), Tennessee roadway system, user-specified models were developed for two major crossings of the Mississippi River (along Interstate Highways 40 and 55) whose seismic performance is vital to the region and to interstate-trucking traffic (Werner and Taylor, 2002).

However, the development of user-specified models for an individual bridge can be time consuming. Therefore, it is impractical to develop such models for most of the large number of more "typical" bridges that comprise a highway system. For such bridges, the default models are much more feasible to implement. Development of improvements to current default bridge modeling procedures is an area of active research (TCW 2003 and 2005).

For pavements and approach fills, the current REDARS™ 2 default models are based on California construction and repair practices. Therefore, they will not adequately characterize the seismic performance of pavements and approach fills for other states whose construction or repair practices will differ from those in California. Under such conditions, user-specified models that reflect these differing practices should be used.

2.3.3.3 Input Data for Default Bridge Models

The National Bridge Inventory (NBI) database is the only electronic database of attributes that is available for bridges nationwide (FHWA 2003). For this reason, the default bridge models currently included in REDARS™ 2 are based on the NBI database. In REDARS™ 2, the NBI data needed for analysis of the bridges in the particular system being analyzed are obtained through the Import Wizard.

The NBI database was developed primarily for bridge-maintenance applications. Therefore, it does not include much of the bridge-attribute data that would ordinarily be needed for seismic analysis. This was a constraint during the prior development of the default bridge models that are currently included in REDARS™ 2.

2.3.3.4 Bridge Overpasses

REDARS™ 2 estimates effects of bridge damage on traffic flows, not only along the roadway that the bridge is on, but also along any underlying roadway(s). However, the federal databases that are accessed by the Import Wizard do not specify whether a bridge crosses over a roadway, nor do they identify the underlying roadway(s). Therefore, REDARS™ 2 users must specify which bridges cross over an underlying roadway, together with the link numbers for the portion of each underlying roadway that is beneath the bridge.

2.3.3.5 Retrofitted Bridges

In many earthquake-prone regions of the United States, programs are underway to improve the seismic performance of vulnerable bridges by means of column-jacket retrofits. REDARS™ 2 can represents the beneficial effects of column jacketing by modifying the default bridge model as described in Chapter 4. However, the NBI database does not identify those bridges that have been column-jacketed. Therefore, the user must identify each retrofitted bridge in the highway system, as input to REDARS™ 2.

2.3.3.6 Use of Component Traffic States to Develop System States

After each component's traffic states at various post-earthquake times are obtained, they are incorporated into the highway system's network model in order to develop overall post-earthquake "system states" at each of these times. The system states consist of modified highway systems (relative to the pre-earthquake system) that now incorporate reduced traffic states of the various links in the system that have been damaged during the earthquake. These system states must also include the effect of each component's damage state on adjacent and underlying roadways. This, in turn, will depend on the level of damage to the component, and also on the component's location within the system. These system states are used by the REDARS™ 2 network-analysis procedure described in Chapter 5 and Appendix I, in order to estimate system-wide travel times and trip demands at each post-earthquake time.

2.3.4 ECONOMIC MODULE

The Economic Module contains a first-order model for estimating repair costs and economic losses due to increased travel times and reduced trip demands. Broader economic impacts of earthquake-induced travel-time increases and reduced trip-demands (i.e., their effects on businesses, stakeholders, and the regional/national economy) are not included. This module is further described in Chapter 6.

2.4 ANALYSIS PROCEDURE

This section summarizes the various analysis steps shown in Figure 2-1.

2.4.1 STEP 1. INITIALIZATION

Step 1 involves the development of input data that defines: (a) the highway system to be analyzed; (b) the attributes and locations of the various components that comprise this system, together with the soil conditions at the site of each component; (c) origin-destination zones and pre-earthquake trip demands; and (d) various modeling, analysis, and output options. These data are obtained from the Import Wizard, an earthquake walkthrough table, or user-specified input. In addition, calculation of a parameter named lambda -- which establishes the frequency of occurrence of damaging earthquakes within the full duration of the walkthrough table -- is computed. This parameter is needed for subsequent REDARS™ 2 calculation of confidence intervals for the loss results, under Step 3 of this analysis procedure.

2.4.1.1 Data from Import Wizard

The input data that defines the highway system, the bridge attributes, site-specific soil conditions needed to estimate ground-motion hazards, and origin-destination zones and pre-earthquake trip tables developed through the REDARS™ 2 Import Wizard, as summarized earlier in this chapter and further described in Appendix C and in Cho et al. (2006b).

2.4.1.2 Walkthrough Table Data

Earthquake scenarios are provided in terms of a walkthrough table. For each year within a total walkthrough duration that can be on the order of thousands or tens-of-thousands of years, this table prescribes the number of earthquakes occurring during that year, the location of each earthquake and whether it is caused by rupture along a known fault or an unknown (i.e., randomly-defined) fault, the moment magnitude of each earthquake, and the location and relevant attributes of the causative fault. This table is developed prior to the REDARS™ 2 analysis, using established regional earthquake models that account for the region's seismologic and geologic characteristics. Thus far, walkthrough tables have been developed for coastal California and for the region of the Central United States region that surrounds the New Madrid seismic zone. These walkthrough tables are described in Appendix B.

2.4.1.3 Other User-Provided Data

Other input data to be provided by the user during this initialization step are: (a) identification of potentially liquefiable sites within the highway system, and input soils data needed for the REDARS™ 2 analyses of earthquake-induced liquefaction hazards at these sites; (b) identification of column-jacketed bridges; (c) identification of bridges that cross over other roadways, along with the link number for the underlying bridge; (d) unit cost data, in units of dollars per unit travel-time-delay; and (e) modeling, analysis, and output options. These latter options include: (f) whether the analysis is to be deterministic or probabilistic; (g) user-specified models to be used for any components in the network; (h) identification of bridges and other components for which seismic-hazard and/or component-damage probabilities are to be monitored; (i) identification of origin-destination zones for which access and egress times and/or trip attraction and production are to be monitored; and (j) identification of lifeline routes along which travel times are to be monitored.

2.4.1.4 "Lambda" Calculations

After the highway-system model, bridge-attribute data, soils data, and earthquake walkthrough table are provided, and if the SRA is to be probabilistic, REDARS™ 2 initially performs an analysis that identifies those years within the walkthrough table during which at least some bridge damage occurs. Then, a parameter named "lambda" is calculated as the ratio of this number of years during which such damage occurs to the total number of years in the walkthrough table. This "lambda" parameter is used in the subsequent estimation of confidence intervals for the loss results (under Step 3 of the REDARS™ 2 methodology). Only those years during which some bridge damage occurs are further analyzed in the later steps of the SRA.

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2.4.2 STEP 2. SYSTEM ANALYSIS

Step 2 consists of a full system analysis for one particular scenario earthquake and one set of site, component, and system parameters. If the SRA is to be deterministic, these input parameters can consist of either median values or one set of randomly selected values of parameters whose uncertainties have been modeled. For probabilistic SRA applications, this single analysis represents one simulation -- which is one set of loss results corresponding to one earthquake in the walkthrough table and one set of randomly selected parameters whose uncertainties have been modeled.

For the earthquake considered in Step 2, the system analysis consists of the following evaluations:

- *Hazard Evaluation.* First, the data and models contained in the Hazards Module are used to estimate the earthquake ground motion and PGD hazards throughout the system.

- *Direct Loss and System State Evaluation.* Once the ground motion and PGD hazards are estimated, the data and models from the Component Module are used to evaluate direct losses and system states (defined at various times after the earthquake).

- *Transportation Network Analysis.* The data and transportation network-analysis procedure from the System Module are applied to each post-earthquake system state, in order to estimate (a) system-wide travel times and trip demands; (b) access/egress times to/from key locations identified under Step 1; and (c) travel times along key lifeline routes also identified in Step 1. Differences between these post-earthquake results and pre-earthquake travel times measure how earthquake damage to the system affects its ability to carry traffic.

- *Economic Impact Evaluation.* The data and models from the Economic Module are applied to the above post-earthquake travel-time delays and trip demands, in order to estimate repair costs and losses due to travel time delays and trips foregone.

2.4.3 STEP 3. CHECK NEED FOR ADDITIONAL SYSTEM ANALYSIS

The operations under Step 3 will depend on whether the SRA is deterministic or probabilistic. If the SRA is deterministic, another analysis is carried out only if the user wishes to consider another scenario earthquake or input parameter variation (e.g., if deterministic sensitivity studies are being carried out). Otherwise, the deterministic analysis is ended.

If the SRA is probabilistic, Step 3 uses procedures described in Appendix J of this report to estimate confidence intervals (CIs) for the results from all simulations developed thus far. These CIs are then displayed for consideration by the user. If the user decides that these CIs are not yet acceptable, the SRA then develops another simulation by repeating the system analysis under Step 2 for a new earthquake scenario and a new set of randomly selected values of the uncertain parameters. When the CIs are judged to be acceptable, the SRA then proceeds to the final aggregation of all probabilistic results under Step 4 (as summarized in Section 2.4.4).

2.4.4 STEP 4. AGGREGATE RESULTS

Step 4 is carried out only if the SRA is probabilistic. If so, the results from all simulations are compiled and probabilistic aggregations of these results are developed. Such probabilistic results can be developed for: (a) economic losses due to highway-system damage; (b) ground-motion hazards at any component site previously identified under Step 1; (c) damage states for any component previously identified under Step 1; (d) increases in access/egress time and/or reductions in trip attraction/production for any key location previously identified under Step 1; and (e) travel time increases along any key lifeline route previously identified under Step 1.

When these aggregations are completed, the probabilistic SRA is terminated. These aggregations and the overall probabilistic SRA process are illustrated in a demonstration application of REDARS™ 2 to an actual highway system that is documented in Chapter 7.

2.5 USE OF SRA RESULTS FOR SEISMIC RISK REDUCTION DECISION MAKING

This development of the REDARS™ 2 software has been largely motivated by the need for a tool that can bring system-wide seismic risk issues into the decision-making process for establishing appropriate pre- and post-earthquake seismic risk reduction programs for a highway system. This important type of REDARS™ 2 application was first addressed in Section 1.4.2 and is further discussed here.

Table 2-1 summarizes the types of seismic-risk-reduction decisions that can be guided by REDARS™ 2 applications. One approach for using REDARS™ 2 in this way is through an acceptable-risk decision-guidance process. The process is based on the recognition that it is not possible to achieve a "zero seismic risk;" i.e., regardless of what degree of seismic risk reduction is implemented, there will always be some residual risk of unacceptable seismic performance of the highway system. An "acceptable" level of seismic risk is that level for which the costs to further reduce these residual risks are no longer acceptable.

The steps that comprise this process are shown in Figure 2-4 and are described in the remainder of this section. The demonstration application of REDARS™ 2 to an actual highway system that is described in Chapter 7 provides an example of the use of REDARS™ 2 results in this way.

2.5.1 STEP 1. IDENTIFY SEISMIC DECISION ALTERNATIVES

Under Step 1, the various options that are available to decision-makers as possible strategies for reducing seismic risks to the highway system are identified. In addition to the various measures listed in Table 2-1, other measures could include (a) financial planning to ensure adequate funds for emergency response and recovery operations, and to establish appropriate funding levels for seismic risk reduction; and (b) coordination with FEMA and other federal agencies to streamline the post-earthquake procurement of funds for highway-system repair and recovery.

Table 2-1. Uses of Highway System SRA for Seismic Risk Reduction Decision Making

Strategy	Description
Prioritization of Bridges for Seismic Retrofit	Evaluation of what retrofit sequence should be adopted for various bridges in the region, in order to optimize the benefits of the retrofit to the seismic performance of the highway system. SRA would be applied for different retrofit sequences, and would assess which sequence leads to the optimum seismic performance of the system.
Establishment of Design Acceleration Level for Bridge Design or Retrofit	Selection of alternative design acceleration levels should be considered for design of a new bridge or retrofit of an existing bridge. This should consider the initial construction costs associated with each design acceleration level, the potential for bridge damage, and its impact on the seismic performance of the highway system.
Emergency Response Planning	Evaluation of effects of various seismic decision options on access/egress times to or from key locations (e.g., hospitals, fire stations, airports, emergency command centers, centers of commerce). This could guide establishment of seismic retrofit priorities and design acceleration levels for components along emergency response routes. SRA can also be used in real-time assessment of seismic performance of a highway system after an actual earthquake, to guide real-time emergency response decision making.
Assessment of Available Repair Resources	Roadway downtimes due to earthquake damage will depend on available equipment, material, and labor for repair. SRA can assess how losses due to travel time delays are affected by these downtimes, and optimal repair resources for reducing these losses, by considering relative costs and benefits of various repair resource options.
System Enhancement	Assessment of how construction of new roadways that are being planned could improve the seismic performance of the highway system, as well as the effectiveness of possible short term traffic management strategies (e.g., conversion of selected roadways from one-way to two-way traffic) in improving system performance.

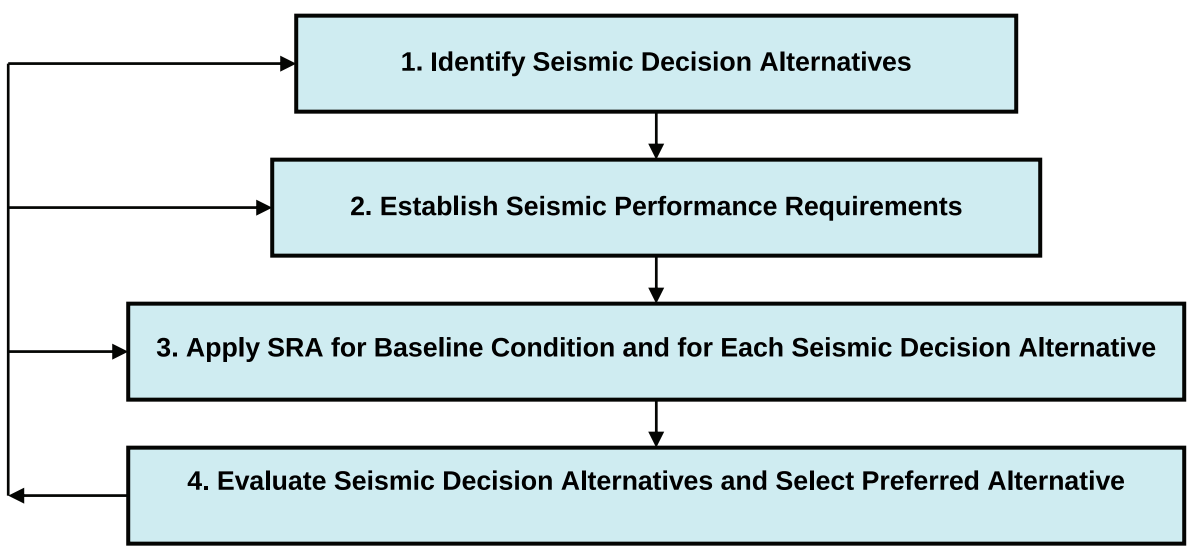


Figure 2-4. Use of SRA Results for Seismic Risk Reduction Decision Making

2.5.2 STEP 2. ESTABLISH SEISMIC PERFORMANCE REQUIREMENTS

Under Step 2, decision makers would tentatively select types and forms of SRA results that will be used to evaluate the seismic decision alternatives. This selection can consider input from stakeholders in the seismic performance of the highway system, such as: (a) federal, state, and local transportation officials -- who may wish to focus on performance requirements that minimize repair costs and downtimes of the highway system; (b) emergency response planners -- who may wish to include performance requirements that address acceptable levels of travel time delays to/from critical facilities; and (c) business and civic leaders -- who may wish to include performance requirements based on accessibility to/from regional commercial centers, etc.

The performance requirements may be either deterministic or probabilistic. For example, deterministic requirements could consist of acceptable levels of loss for a designated Level 1 earthquake (a moderate and frequently occurring event), and for a Level 2 earthquake (a severe and infrequently occurring event). Probabilistic requirements may consist of acceptable probabilities of exceedance for designated levels of loss due to highway system damage, or acceptable means and variances of total losses. In this, the losses should be computed as the present value of the initial cost for implementing the seismic decision alternative (e.g., the initial construction cost associated with a given design acceleration level), the post-earthquake repair costs, and the post-earthquake losses due to increased travel times and reduced accessibility to key locations in the region.

When establishing acceptable-risk levels and corresponding seismic-performance requirements, one must consider the initial costs needed to meet such requirements (e.g., initial costs of construction for alternative levels of design acceleration for retrofit of an existing bridge) as well as potential losses due to earthquake-induced damage of the highway system.

A systematic approach for obtaining an acceptable level of seismic risk uses evaluation of means and variances of total life-cycle costs for various seismic decision options (Werner et al. 1997; Ferritto et al., 1999; Werner et al., 2002). Features of the approach are:

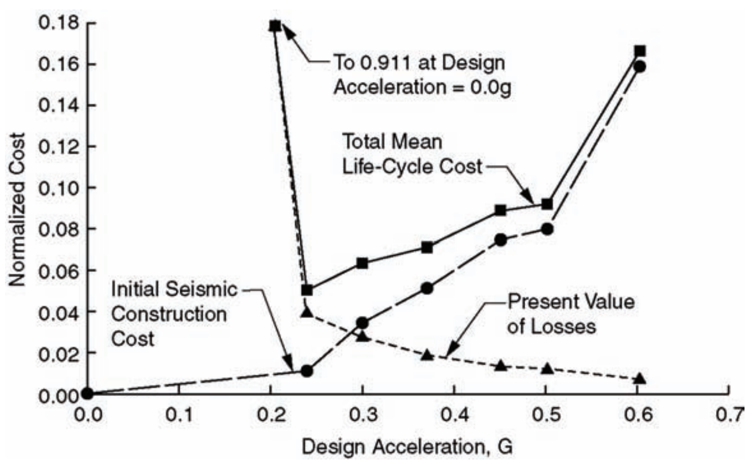
- It estimates total life-cycle cost for each seismic-decision alternative which, as previously noted is computed as the present value of: (a) the initial cost for implementing the alternative (e.g., cost of construction associated with different design acceleration levels for a bridge); (b) post-earthquake repair costs; and (c) post-earthquake losses due to increases in travel time reductions in trip demands, or reduced access to key locations. Where higher-order economic losses can be estimated, they can also be included in this total cost computation.

- Mean values and variances of these life-cycle costs are computed through statistical analysis of the life-cycle costs associated with a given seismic decision alternative, as obtained from probabilistic SRA of that alternative for each scenario earthquake and simulation.

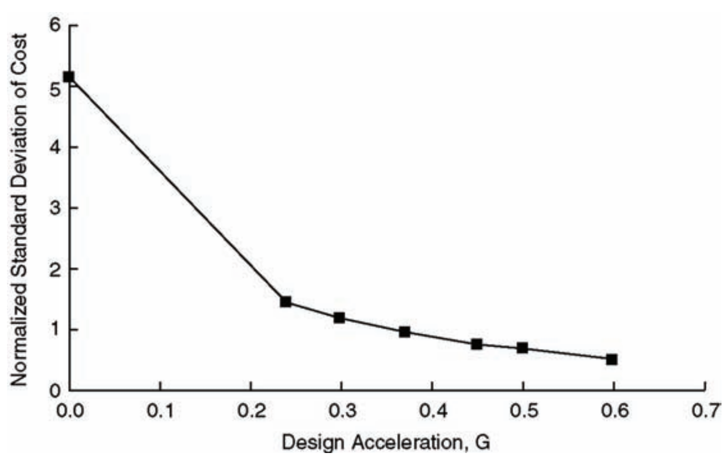
- Seismic decision alternatives are treated as “investments” in seismic risk reduction. One basis for evaluating an investment is in terms of its financial yield. In this SRA application, a higher “yield” of an investment in seismic risk reduction is viewed being analogous to minimizing the mean value of the total life cycle cost. In addition, a prudent investor evaluates his/her investments not only in terms of their yield but in also in terms of their safety. In this, the safety (or reduction in volatility) of an investment in seismic risk reduction can be viewed in terms of lowering the variance (or standard deviation) of the life-cycle costs to an acceptable level.

- Figure 2-5 shows how this approach was used to establish a design acceleration level for a wharf structure at a major seaport in California. In this case, the decision-makers opted to use a design acceleration level of about 0.45 g, which is higher than the design acceleration at the minimum value of the life-cycle cost (which is about 0.25 g). This was based on their desire for reduced volatility in the seismic performance of this wharf. (Werner et al., 1997).

- Figure 2-6 shows how SRA results can be used to guide the establishment of priorities for retrofit of a several bridges within a highway system. In this, alternative priorities are evaluated in terms of the means and standard deviations of the resulting total costs. The dashed line in this figure shows those prioritization plans with the most favorable combinations of mean and variance (i.e., the lowest values of these quantities).



a) Mean Value of Total Life-Cycle Cost



b) Volatility (Standard Deviation) of Total Life Cycle Cost

Figure 2-5. Selection of Design Acceleration for a Wharf Structure (Werner et al., 1999)

2.5.3 STEP 3. APPLY SRA FOR BASELINE CONDITION AND FOR EACH SEISMIC DECISION ALTERNATIVE

Under Step 3, SRA of the highway system is carried out for each earthquake event and simulation identified for consideration under the seismic performance requirements for the system (from Step 2).

2.5.3.1 Baseline System Performance

The SRA application starts with the development of a set of baseline system performance results. These baseline results should consist of:

- *Pre-Earthquake Performance of Existing Highway system.* The REDARS™ 2 transportation network analysis procedure is used in the Import Wizard to assess the pre-earthquake traffic flows, travel times, and costs of travel for the existing (undamaged) highway system.

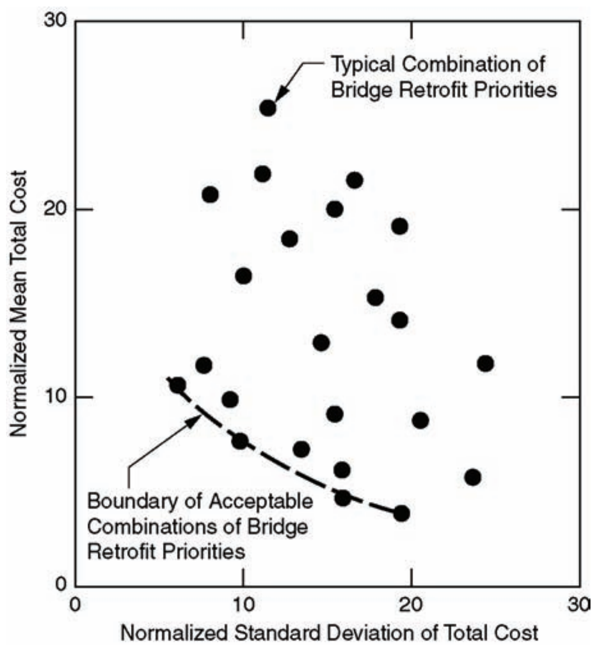


Figure 2-6. Illustrative Results for Evaluation of Alternative Bridge Retrofit Priorities

- *Post-Earthquake Performance of Existing Highway system.* Scenario earthquakes are applied to the existing highway system (before any seismic decision alternatives are considered), and SRA is carried out to evaluate post-earthquake traffic flows, travel times, and travel costs.

- *Baseline Results.* The pre- and post-earthquake performance of the existing highway system is compared in order to indicate the potential risks and losses that could occur in the absence of seismic risk reduction.

2.5.3.2 Post-Earthquake System Performance for Each Decision Alternative

Once the baseline system performance results are developed, it remains to carry out SRA of the highway system after each seismic decision alternative is implemented. To illustrate this process, suppose that the objective of the SRA is to establish appropriate levels of design acceleration for the upgrade of a major bridge for which seismic retrofit is planned. Also, suppose that five different levels of design acceleration have been identified as seismic decision alternatives in Step 1. Then, SRA of the highway system is carried out for cases in which the bridge is retrofitted to correspond to each of the alternative design acceleration levels. The resulting losses due to damage to the highway system after the bridge is retrofitted to each design acceleration level (due to repair costs, travel time delays, etc.), and the initial cost of construction for that design acceleration level, are used in Step 4 to evaluate the various design acceleration levels being considered.

2.5.4 STEP 4. EVALUATE SEISMIC DESIGN ALTERNATIVES AND SELECT PREFERRED ALTERNATIVE

Under Step 4, the SRA results for the baseline (existing) condition and for each seismic decision alternative are evaluated and compared. From this, a preferred alternative is selected. Stakeholder interaction in evaluating system performance goals relative to this overall decision-making process should be an important element of this step. On the basis of this interaction, it is possible that additional seismic decision alternatives may be identified, the seismic performance requirements for the highway system may need to modified, and/or additional SRAs may need to be implemented for additional cases or decision alternatives. If this occurs, one or more of the previous steps of the procedure may need to be repeated (see Figure 2-4).

CHAPTER 3: EARTHQUAKE MODELING AND HAZARDS MODULE

3.1 OBJECTIVE

The seismic hazards imposed on a highway system will depend on the magnitudes, locations, and frequencies of occurrence of earthquakes in the region, and on the local geology and soil conditions throughout the system. This chapter summarizes how earthquake scenarios are modeled in REDARS™ 2. It also describes the main elements of the REDARS™ 2 Hazards Module, which contains the data and models necessary to characterize the seismic and geologic hazards throughout the highway system due to each scenario earthquake and simulation. The hazards now included in this module are ground motions, liquefaction, and surface fault rupture. For each hazard, this chapter summarizes: (a) the hazard and its possible effects on highway systems; (b) methods for evaluating the hazard at each component site; and (c) the input data needed to implement the hazard evaluation procedure.

3.2 SCENARIO EARTHQUAKES

3.2.1 OVERVIEW

In a SRA of any lifeline system with spatially dispersed components, individual scenarios are needed to evaluate correlation effects of earthquakes -- i.e., the simultaneous effects (including systemic consequences of damage) of individual earthquakes on components at diverse locations. REDARS™ 2 enables users to specify earthquake scenarios in three ways: (a) as a walkthrough table of earthquake occurrences over time that are based on established regional earthquake models; (b) as an earthquake with an arbitrary user-specified moment magnitude and epicentral location; and (c) as an earthquake with ShakeMap estimates of regional ground motions. Section 3.2 addresses one of these earthquake designations -- the earthquake walkthrough-table.

An earthquake walkthrough table is developed during the initialization of the SRA methodology (Section 2.4.1). It is based on the use of random sampling of an established regional earthquake model to estimate earthquake occurrences during each year of a multi-year walkthrough duration. Each earthquake occurrence during each year of the walkthrough table is represented in terms of its moment magnitude, location, and causative fault attributes, and the table's earthquake occurrences over time represent the regional model's estimation of frequencies of earthquake occurrence. The table is used in a walkthrough analysis procedure for probabilistic SRA in REDARS™ 2 (Daykin et al., 1994). This procedure facilitates development of loss distributions from the SRA, estimation of confidence intervals for the loss results, and display of their variability over time.

3.2.2 REGIONAL EARTHQUAKE SOURCE MODELS

The REDARS™ 2 SRA methodology incorporates regional earthquake source models that have been adapted from models used by the United States Geological Survey (USGS) during their development of seismic hazard maps for the conterminous United States (Frankel et al., 2002). The USGS models have been selected because of their development by recognized earth scientists and because of their subsequent extensive external review process. These models incorporate: (a) smoothed historical seismicity as one component of the hazard calculation; (b) a weighted combination of alternative models with different reference magnitudes, as well as large background zones based on broad geologic criteria; and (c) the use of geologic slip rates to estimate earthquake recurrence times for faults in the Western United States.

Thus far, earthquake walkthough tables have been developed for Coastal California and the Central United States (CUS), as described in Appendix B. The Coastal California walkthrough table is used in the demonstration SRA of the northern Los Angeles, California highway system that is described in Chapter 7. Future work will adapt the USGS models to other regions of the United States, so that REDARS™ will contain an extensive, consistent, and technically-robust set of walkthrough tables for earthquake-prone regions throughout the country.

3.2.3 WALKTHROUGH ANALYSIS PROCEDURE

The following paragraphs summarize the REDARS™ 2 walkthrough analysis procedure for probabilistic SRA applications. This procedure is further described in Appendix A.

3.2.3.1 Step 1. Total Duration of Walkthrough Table

In Step 1, the user selects the total time duration of the earthquake walkthrough table. This duration will typically be in the thousands of years. As noted in Chapter 2, the number of years actually considered in the walkthrough table may include only a segment of this total time duration if, for this segment, it turns out that the confidence intervals for the loss results are acceptable to the REDARS™ 2 user.

3.2.3.2 Step 2. Scenario Earthquakes during Each Year of Walkthrough

Step 2 generates the earthquake walkthrough table with the above duration. This is done first for Year 1, and then for each succeeding year of the walkthrough. For each year, a series of uniform random numbers is generated and used with various earthquake probability distributions developed from regional earthquake models (Sec. 3.2.2), in order to establish: (a) the number of potentially damaging earthquakes -- i.e., earthquakes with moment magnitude (M_w) ≥ 5.0 -- that have occurred somewhere in the region during the year; and (b) the location and the magnitude of each of these earthquakes. The table also includes the attributes of the causative fault for each earthquake (see Sec. 3.5.2.2). For earthquakes caused by rupture along known active faults, these attributes are estimated from regional fault-specific data. For earthquakes in the walkthrough table whose source is designated as "random" (i.e., the causative fault is unknown), fault attributes are estimated from regional seismologic and tectonic data (see App. B).

Note that, for the demonstration SRA of the northern Los Angeles, California highway system that is described in Chapter 7, the analysis allows for the possibility that more than one potentially damaging earthquake can occur during a single year. For other regions of the United States that are less seismically active, this possibility is more remote.

3.3 GROUND MOTION HAZARDS

3.3.1 HAZARD DESCRIPTION

Past earthquakes have shown that highway components can be susceptible to damage from strong ground shaking. The extent of this damage depends not only on the geometry and structural characteristics of the component, but also on the amplitude, frequency content, and duration of the ground shaking. Past earthquakes have also shown that the spatial distribution of ground shaking throughout a system will depend on the nature of the fault-rupture process, the travel paths followed by the seismic waves as they propagate from the earthquake source and throughout the highway system, and the local soil conditions within the system. Furthermore, empirical studies of recorded ground motions have shown that this distribution of ground shaking is not random; rather, it tends to attenuate with increasing distance from the seismic source and is usually most severe in soft soil deposits. In addition, for a given source-site distance and site conditions, the ground motions tend to increase with increasing earthquake magnitude, except for large magnitude earthquakes where saturation of the ground-motion amplitudes tends to occur. The estimation of ground shaking hazards is essential not only to evaluate the potential for system and component damage from these hazards, but also to assess other collateral hazards such as liquefaction.

3.3.2 HAZARD EVALUATION PROCEDURE

The procedure used to estimate earthquake ground motions for SRA of a highway system must account for the seismologic, geologic, and tectonic characteristics of the region and the local conditions at each component site throughout the system. Documentation of various approaches for considering these factors in the estimation of site-specific ground motions is readily available in the technical literature (e.g., Housner and Jennings, 1982; Seed and Idriss, 1982; Kramer 1996; Campbell 2003).

3.3.2.1 Model Overview

REDARS™ 2 uses ground-motion attenuation models to estimate ground motions at each component site due to each earthquake in the walkthrough table. This is because such models are plentiful and are the most practical approach available for rapid estimation of ground motions for the large number of sites and the many earthquakes that will need to be considered in a probabilistic SRA of a highway system.

Ground-motion attenuation models estimate site-specific ground motion by using an equation that includes terms to account for the earthquake's magnitude and distance from the site, local site conditions and, in many cases, hanging-wall, foot-wall, and directivity effects. Terms for representing uncertainties in the ground-motion predictions are also included in these equations.

3.3.2.2 Model Differences

Many different attenuation models are used in current practice (e.g., Campbell 2003 summarizes several of these models). Different models are used for different regions of the country, in order to account for regional differences in tectonic characteristics. For example, because the Eastern and Central United States is more tectonically stable than the West, earthquakes in the East and Midwest are usually associated with higher stress drops and lower attenuation rates. This results in larger ground-motion amplitudes at short periods and large distances for earthquakes in the eastern and central regions of the country.

There are also differences between ground-motion models for a given region, due to differences in assumptions, data, and analysis procedures used to develop the various models. For example, the various ground-motion models developed for California earthquakes, where strong motion recordings are most plentiful, model differences arise because of: (a) different databases of the strong motion recordings used to develop the models; (b) different procedures for statistically analyzing the records from these databases; (c) different definitions of magnitude, distance, and site conditions; and /or (d) different definitions of ground-motion output from the model (i.e., some models may be based on statistical analysis of the largest component of horizontal motion recorded at a given station, whereas other models may be based on the average of the two horizontal components). In general, for comparable definitions of ground-motion output, most ground-motion models for California earthquakes provide reasonably similar ground-motion estimates when applied for ranges of magnitudes, distances, and site conditions where recorded motions are most plentiful. However, for other ranges of these parameters where ground-motion records are sparse, the ground-motion predictions by the various models can differ substantially.

Models for predicting ground motions in the central and eastern United States do not have the benefit of strong motion recordings that can provide a statistical basis for these models. Instead, the models have been developed from a variety of other methods such as: (a) statistical analysis of seismologically-based estimates of strong ground motion (e.g., Atkinson and Boore, 1995; Toro et al., 1997); (b) modifications of attenuation relationships from the western United States that were based on seismological estimates of ground motions from the western and eastern United States (e.g., Campbell 2003); and/or (c) consideration of qualitative effects of historical earthquakes that have been documented. Because of the lack of recorded strong motions on which to base these models, uncertainties in predicting ground motions in the Central and Eastern United States are much greater than for western United States.

3.3.2.3 Model Output

Output from the ground-motion attenuation models is provided as spectral accelerations for a range of natural periods (including the zero-period spectral acceleration which is equal to the peak acceleration). However, it is necessary to save spectral accelerations only for those periods that are used in the various geologic-hazard and component damage-state models that require ground-motion input data. In REDARS™ 2, spectral accelerations at periods of 0.3 sec. and 1.0 sec. are used in the default bridge damage-state model, and the peak ground acceleration is used in the liquefaction hazard model. If user-specified bridge models are used that require spectral accelerations at other natural periods, these spectral accelerations will also need to be saved.

It is, of course, important that the spectral acceleration output from the ground-motion attenuation model be consistent with the ground-motion input needed for the component damage-state and geologic-hazard models that are to be applied in REDARS™ 2. That is, if the ground-motion model provides output as the average of the two components of recorded horizontal motion (instead of the maximum value), the damage state or geologic hazard models that use this data should be based on the same definition. Most current ground-motion models provide output as the average of the two horizontal components. Unfortunately, current bridge damage models often do not make this distinction (Baker and Cornell, 2006).

3.3.3 INPUT DATA

Input data for modeling earthquake ground-motion hazards at a given site in the highway system consist of: (a) the earthquake's moment magnitude; (b) the distance from the site to earthquake source; (c) the local soil conditions at the site; and possibly (d) other data, such as hanging-wall and foot-wall locations, and directivity parameters.

In REDARS™ 2, the moment magnitude for each scenario earthquake is specified in the earthquake walkthrough table, along with various parameters needed to compute source-site distances. These parameters include: (a) epicenter location; (b) depth to hypocenter and to seismogenic zone; (c) latitude, longitude, and depth of center of energy release; (d) fault type; (e) length, width, azimuth, and dip of each segment of the fault rupture plane; (f) direction of rupture along fault plane; and (g) zone of deformation due to fault rupture (if specified by the user). These quantities enable REDARS™ 2 to compute a wide variety of source-site distances, thereby enabling it to accommodate not only the ground-motion models that are currently included in REDARS™ 2, but also a wide variety of other models that may be added in the future. These source-site distance calculations are further described in Section D.2 of Appendix D.

The various ground-motion attenuation models typically characterize effects of local soil conditions by a single term in the ground-motion equation. In these models, local site conditions are represented either as NEHRP soil categories or as other categories that can be converted to the NEHRP categories. As described in Appendix C, the Import Wizard can accommodate digital NEHRP soils data, if such data are available for the region being analyzed and if: (a) the data are based on local geology and shear wave velocity and are provided in ESRI Shapefile format; (b) the data are in a geographic coordinate system; and (c) the datum matches that of the National Highway Planning Network (NHPN) base data, which are currently in NAD 1927. If such digital data are not available, the user must provide the NEHRP soil-category input data for all component sites in the highway system. For this situation, these estimates should be based on: (a) available topographic maps, quaternary-geologic maps, and maps with depth-to-bedrock contours throughout the system area; (b) available soil test data obtained along or near the highway system; and (c) correlation of the geologic units from the geologic maps with the various soil categories indicated by the soil test data.

3.3.4 CURRENT REDARS™ 2 GROUND MOTION MODELS

REDARS™ 2 now includes two ground-motion models. These models are briefly summarized below and are further described in Sections D.3 and D.4 of Appendix D.

3.3.4.1 Abrahamson-Silva (1997) Model

The Abrahamson-Silva (1997) ground-motion model applies to shallow crustal earthquakes in active tectonic regions of the western United States. Its main features are summarized below:

- It expresses the ground motion as a function of the earthquake magnitude, source-site distance, local soil conditions, type of faulting, whether the site is along the hanging wall of footwall of the ruptured fault plane, and inter-event and intra-event uncertainties.

- It computes spectral accelerations of horizontal and vertical ground motions at 28 periods that range from 0.01 sec. to 5.0 sec. The horizontal spectral acceleration represents the average of the two components of horizontal motion recorded during the various earthquake events cited in the Abrahamson-Silva (1997) paper.

- It uses moment magnitude to represent earthquake magnitude, and defines the source-site distance as the closest distance from the site to the rupture plane. Local soil conditions are characterized using two site classifications: (a) rock site, which has a soil thickness of less than 20 m that overlies rock; and (b) deep soil site, with soils whose thickness exceeds 20 m.

- It also includes: (a) a “style-of-faulting factor that accounts for whether the causative fault is reverse or strike-slip; and (b) a “hanging wall” factor that models differences between ground motions recorded on the hanging wall or foot wall of a dipping fault.

3.3.4.2 Silva et al. (2002 and 2003) Model

The Silva et al. (2002 and 2003) model applies to stable tectonic regions of the central and eastern United States. It has the following main features:

- The computation of ground motions involve the following steps: (a) computation of earthquake motions in hard rock (NEHRP Type A sites) as a function of earthquake magnitude and source-site distance; (b) conversion of these hard rock motions to corresponding motions in firm rock (NEHRP Type B sites); (c) development of a soil amplification factor relative to firm-rock motions; and (d) use of this factor, together with the firm-rock motions from Step b, in order to estimate site-specific ground motions including effects of local soil conditions and uncertainties.

- It uses moment magnitude to represent earthquake magnitude, and defines the source-site distance as the closest distance from the site to the surface projection of the rupture surface. Soil amplification factors are tabulated for different NEHRP site classifications and, for each classification, are provided as a function of the peak acceleration in firm rock.

- Hard rock motions are estimated from numerical simulations using a stochastic point-source model. The hard rock motions are computed in terms of medians and standard deviations that are estimating by weighting results from a single-corner model with variable stress drop and a double-corner model with saturation.

3.3.4.3 Future Direction

Future versions of REDARS™ will include a library of ground-motion models for various regions of the United States, to provide users with a choice when selecting a model that they view as being most appropriate for their particular application. Furthermore, in addition to using a single model, users will also be able to estimate site-specific ground motions as a weighted average of estimates from multiple models built into REDARS™ for a given region.

3.4 LIQUEFACTION HAZARDS

3.4.1 HAZARD DESCRIPTION

Liquefaction is a process that occurs in loose, saturated, granular soil materials subjected to earthquake ground shaking. If this shaking is of sufficient strength and duration, the soils tend to decrease in volume due to a collapse of the soil "skeleton." This volume change is restricted by the rate at which the pore water can flow out of the soil, thereby resulting in a dramatic increase in pore-water pressure and a temporary loss of soil stiffness and shear strength when the pore water pressure approaches the in-situ vertical effective stress. Liquefaction-induced soil failure can result in lateral spread displacement and vertical settlement, reduced bearing strength, increased lateral pressures against retaining structures (e.g., abutment walls), and a loss of frictional resistance of pile elements at their interface with liquefied soils layers.

3.4.2 HAZARD EVALUATION PROCEDURE

The REDARS™ 2 procedure for estimating liquefaction hazards was chosen with two objectives in mind. First, the procedure was to be technically sound and based on well-established liquefaction hazard evaluation methods. The second objective addressed the absence of electronic databases of soil attributes that would facilitate the development of input data for liquefaction hazard analysis. Therefore, these input data will need to be compiled by the REDARS™ 2 user. The effort to compile these input data could be formidable, if the highway system includes many potentially liquefiable sites. In view of this, it was determined that technically sound liquefaction hazard analysis method that uses a minimum number of input soil parameters would be most desirable for incorporation into REDARS™ 2.

With this as background, the procedure currently used in REDARS™ 2 to estimate liquefaction hazards is summarized below. The procedure is further described in Appendix E.

3.4.2.1 Step 1. Initial Screening

Step 1 consists of initial screening of soil sites throughout the highway system to identify those sites within the system that are potentially liquefiable. This screening step is performed by the user prior to the start of the REDARS™ 2 application. It is based on the user's assessment of soil properties, water table depths, and site topography, as described in Section E.3. In REDARS™ 2, liquefaction hazards are computed only at those sites within the highway system that are identified as being potentially liquefiable in this initial screening step.

3.4.2.2 Step 2. Lateral Spread Displacement Hazards

Under Step 2, the Bardet et al. (2002) four-parameter model is used to estimate lateral spread displacements at each site in the highway system that was designated as potentially liquefiable in Step 1. An attractive feature of this model for application to large numbers of sites is that it is less input-data intensive than other models that were considered for inclusion in REDARS™ 2.

3.4.2.2(a) Input Data

Input data to the Bardet et al. models consists of

- *Earthquake-Dependent Data*, which are the moment magnitude of the earthquake and the horizontal distance from the site to the earthquake's center of energy release. For sites east of the Rocky Mountains, an equivalent distance for use in the lateral spread calculations is estimated as a function of the moment magnitude and the peak ground acceleration

.

- *Site Topography Data*, which are either the ground slope or, for sites with a free face, the ratio of the height of the free face to the distance from the face to the site (which is termed a "free-face ratio").

- *Site Soils Data*, which is an effective thickness (T_{15}) that is computed as the sum of the thicknesses of all saturated sand layers at the site whose effective blow-count is less than 15.

3.4.2.2(b) Median Value of Lateral Spread Displacement

After these input data are compiled, the Bardet et al. model computes the median value of the natural logarithm of the lateral spread displacement, as a function of the above input parameters.

3.4.2.2(c) Treatment of Uncertainty

The Bardet et al. model includes effects of uncertainties by computing the standard deviation of the natural logarithm of the median displacement, as a function of all of the above input parameters. Then, a normally distributed random number is generated and used with the standard deviation to obtain an uncertainty factor in log space. The above median displacement and the uncertainty factor are added, and the anti-log of this sum represents the lateral-spread displacement including uncertainties, for this particular scenario earthquake and simulation.

3.4.2.3 Step 3. Vertical Settlement

In addition to lateral spread displacements, REDARS™ 2 computes liquefaction-induced vertical settlements at each potentially liquefiable site. The Tokimatsu-Seed (1987) model is used to perform this computation.

3.4.2.3(a) Input Data

The input data for the Tokimatsu-Seed estimate of vertical settlement consist of:

- *Ground Motions.* The site-specific peak ground acceleration computed using the selected ground-motion model from the library of models contained in REDARS™ 2.

- *Soils Data.* For all layers at the site (regardless of whether they are potentially liquefiable), the layer's thickness, depth below the ground surface, total overburden pressure, and effective overburden pressure must be provided. In addition, for layers that are potentially liquefiable, the corrected standard penetration test (SPT) blow-counts must also be specified.

3.4.2.3(b) Vertical Settlement Computation

The Tokimatsu-Seed model consists of a series of curves of cyclic stress ratio vs. corrected SPT blow-count, in which each curve corresponds to a different fixed value of volumetric strain. The REDARS™ 2 adaptation of this model consisted of fitting equations to these curves and then programming the equations into the software. After this was done, the following procedure was used to estimate site-specific vertical settlement for a given earthquake scenario and simulation:

- For a given saturated sandy layer at the site, compute the cyclic stress ratio. Enter the programmed version of the Tokimatsu-Seed curves with this cyclic stress ratio and the layer's corrected SPT blow-count to obtain the layer's median volumetric strain. Then, multiply this volumetric strain by the thickness of the layer to obtain the layer's change in thickness.

- Repeat the above step for all saturated sand layers at the site. After this, compute the vertical settlement for this scenario earthquake and simulation as the sum of the changes in thickness for all of the saturated sand layers.

3.5 SURFACE FAULT RUPTURE HAZARDS

3.5.1 HAZARD DESCRIPTION

Roadway components can be damaged by permanent displacement of the ground surface due to fault rupture. Such displacements may be vertical and/or horizontal, with associated tension fissures or compression bulging. The direction and amount of ground movement will depend on the type of faulting, the magnitude and depth of the earthquake, and the complexity of the fault zone. For strike-slip faults, the zone of deformation often includes one or more primary fault strands that contain most of the ground displacement. For thrust or reverse faults, the width of the deformation zone may vary from a single fault strand to a broad zone of primary/secondary deformation on the hanging wall (i.e., the rock and soil above the fault) in excess of 300 ft.

The surface fault rupture hazard will be limited to locations where the rupture approaches and reaches the ground surface and, as a result, this hazard will be much more localized than will ground shaking hazards. Also, surface fault rupture is most likely to occur in regions whose earthquakes typically have a shallow focal depth, such as California and the Wasatch Fault zone in Utah. Surface fault rupture is unlikely in regions of the Eastern and Central United States where the major faults are typically deeply buried.

3.5.2 HAZARD EVALUATION PROCEDURE

For highway systems that are located in regions where surface fault rupture is possible, fault rupture hazards are evaluated by applying the following steps. In REDARS™ 2, surface fault rupture hazards are estimated only for earthquakes included in the walkthrough table. Fault rupture hazards are not estimated for earthquakes that are defined by a user-specified magnitude and point-source location, or by ShakeMap ground-motion maps.

3.5.2.1 Step 1. Initial Screening

Step 1 is carried out by the REDARS™ 2 user before initiating the REDARS™ 2 analysis. It consists of a geologic screening of the region around the highway system to be analyzed, in order to identify active faults in the region that are within or close to the system.

3.5.2.2 Step 2. Permanent Ground Displacement Hazards

For each earthquake in the walkthrough table, REDARS™ 2 uses causative fault attribute and rupture data also contained in the table to identify the extent of the ruptured segment of the fault for this earthquake scenario. Then, each component in the highway system is checked to determine whether it is on or near this fault rupture segment. Permanent ground displacement (PGD) hazards are then computed only for those components found to be on or near the ruptured segment of the fault.

REDARS™ 2 uses the Youngs et al. (2003) model to estimate surface fault rupture hazards. Input data and the REDARS™ 2 procedure for applying this model are briefly summarized below. Further description of this procedure is provided in Appendix F.

3.5.2.2(a) Input Data

All data needed to characterize the causative fault in order to estimate surface fault rupture hazards are provided in the earthquake walkthrough table. As noted in Section 3.3.3, these data consist of: (a) the moment magnitude of the earthquake; (b) the location of the epicenter; (c) the depth to the hypocenter and to the seismogenic zone; (d) the latitude, longitude, and depth of the center of energy release; (e) the fault type; (f) the length, width, azimuth, and dip angle of each segment of fault rupture plane; (g) the direction of rupture along fault plane; and (h) the zone of deformation due to fault rupture (if specified by the user).

3.5.2.2(b) Check whether Component can Undergo PGD due to Fault Rupture (for Probabilistic SRA Application)

REDARS™ 2 generates a series of parameters to determine whether each component may undergo surface fault rupture hazards from this scenario earthquake. These parameters check if any of the following conditions occur:

- The probability of displacement at the site, as computed for this earthquake, exceeds a threshold value (0.004) and a line normal to the fault rupture can be drawn that also extends through the site;

- The site is in a user-specified zone of deformation, if such a zone is defined by the user and input into REDARS™ 2;

- Any line normal to the fault extends through the site, and the site is within 100 m of the fault rupture

- Any line normal to the fault extends through the site, and the site is within 500 m of the hanging wall of the fault; or

- The probability of slip at the site, as computed for this earthquake, exceeds a threshold value of 0.004.

3.5.2.2(c) Calculation of PGD (for Probabilistic SRA Application)

If any of the above conditions occur for any site in the highway system, PGD hazards due to surface fault rupture are calculated for that site. The Youngs et al. (2003) methodology for computing these PGDs relates the occurrence of fault displacement at or near the ground surface to the occurrence of earthquakes (fault slip at depth) in the site region, in much the same manner as is done in a probabilistic seismic hazard analysis (PSHA) for ground shaking. The methodology for this model is taken from PSHA methodology, with the ground-motion attenuation function replaced by a fault displacement attenuation function. In this, the probability of a given level of fault displacement is assumed to follow a beta distribution that depends on the position of the site along the length of the ruptured fault segment. From this, a cumulative probability distribution for fault displacement value is construction for different values of the site's position along the fault. This distribution is then entered with a random number, and the site's PGD for this particular scenario earthquake and simulation is obtained.

3.5.2.2(d) Calculation of PGD (for Deterministic SRA Application)

In REDARS™ 2, surface fault rupture hazards can be estimated for deterministic as well as probabilistic SRA applications. In this, the above cumulative probability curves are simply entered with a probability value of 0.5 (median case), and the corresponding PGD for the site is then estimated.

CHAPTER 4: COMPONENT MODULE

4.1 INTRODUCTION

4.1.1 PERFORMANCE METRICS

This chapter describes the process for characterizing the seismic performance of components for a given earthquake scenario and simulation. In this, two seismic performance metrics are required for use in SRA of highway systems. The first and most important metric is the component's traffic state at various times after the earthquake which, as noted in Chapter 2, represents the component's traffic-carrying capacity at that post-earthquake time. This is most often represented in terms of number of lanes open to traffic although other measures, such as allowable vehicle speed and/or vehicle speed, may also be used.

A second performance metric is the cost for repair of earthquake damage to the components. These costs are estimated separately for each component, and therefore can be obtained without performing a full highway system SRA using REDARS™ 2. They are added to the losses due to system-wide travel-time delays and trips-foregone due to increased post-earthquake congestion, in order to estimate the total economic loss due to earthquake damage to the highway system.

4.1.2 MODELING PROCEDURE

The general procedure for estimating component traffic states and repair costs for a given earthquake scenario and simulation consists of the following general steps:

- ***Damage States.*** After the site-specific ground motion and PGD hazards are computed, the component's damage state is estimated. As noted in Chapter 2, the damage state refers to the extent, location, and type of damage to the component due to the above seismic hazards. These damage-state estimates are typically developed from seismic analysis of a model of the physical component, from statistical analysis of empirical data of component performance during past earthquakes, and/or from expert opinion (or some combination thereof). Ideally, the damage estimates should be provided in terms of metrics that facilitate the subsequent estimation of repair requirements, although this is often not achieved.

- ***Repair Estimates.*** With the component's damage state now established, the next step is to assess how this damage will be repaired, how much it will cost, how long it will take, and whether the component can carry at least partial traffic at any time while the repairs are proceeding. These repair estimates are generally best obtained from engineering and construction personnel with extensive experience in post-earthquake component repair. However, these estimates will depend on the component construction, maintenance, and design practices, as well as available repair resources and experience. These factors can differ substantially from region to region. Therefore, it is typically inappropriate to apply repair estimates for one region of the country to some other region.

- ***Traffic States and Repair Costs.*** With the above repair estimates in place, the component's repair costs and traffic states at various times after the earthquake can be obtained. The traffic state estimates will vary with time after an earthquake, in accordance with the estimated rate of repair of the earthquake damage. As noted in Chapter 2, once the traffic states are obtained for all components in the system, a time-dependent system state (which corresponds to the degree of closure and traffic carrying capacity for all components in the system) is obtained. The transportation network analysis procedure described in Chapter 5 is then used to estimate travel-time delays and trips-foregone for each system state. This information, in turn, is used with the economic model described in Chapter 6 to estimate economic losses due to earthquake damage to the highway system.

4.1.3 DEFAULT AND USER-SPECIFIED MODELS

The damage and repair models summarized in Section 5.1.2 can either be default or user-specified models. The default models use simplified methods to develop first-order estimates of component damage states and time-dependent traffic states, as a function of the level of ground shaking and PGD at the site. They are based on various generic groupings of component types rather than component-specific attributes, and can develop rapid estimates of the performance of the components that are included in each grouping. However, default models do not account for differences in attributes among the various components in each grouping, nor do they account for all of the various component response characteristics that can affect damage-state predictions. They are most appropriate for modeling of components in the highway system which have more-or-less "typical" configurations and structural attributes that are represented by the above groupings. Because this typically constitutes most of the many components in a typical highway system, use of default models will greatly increase the efficiency of the highway system SRA.

As a second modeling option, REDARS™ 2 enables users to provide their own user-specified model as an override to the default model for any component(s) in the highway system. For bridges and tunnels, such models are typically based on detailed seismic analysis that provide a much more refined representation of a component's actual configuration and attributes than do default models. Therefore, user-specified models are particularly appropriate for modeling of those components that have unusual configurations or whose seismic performance is vital to the performance of the overall highway system (e.g., long-span bridges along a major non-redundant highway). However, since such models are usually time consuming to develop, their application to large numbers of components is impractical.

4.1.4 DETERMINISTIC AND PROBABILISTIC MODELS

Models for estimation of component performance can be deterministic or probabilistic. Probabilistic models estimate the cumulative probability of various levels of damage as a function of the applied seismic hazards. They are intended to account for uncertainties in analysis procedure, material properties, and other factors related to seismic performance estimation whose characterization is not certain. Deterministic models do not account for these various uncertainties.

REDARS™ 2 provides default models for three types of components -- bridges, approach fills, and pavements. The default models for bridges are probabilistic, and the default model for approach fills and pavements are deterministic. The remainder of this chapter summarizes these default models, as well as basic principles for development of user-specified models.

4.2 DEFAULT MODELS FOR BRIDGES

This section summarizes the input data and default procedures used in REDARS™ 2 to model the seismic performance of bridges subjected to ground shaking and PGD hazards.

4.2.1 INPUT DATA

4.2.1.1 Data Needs

Ideally, input data for analysis of the seismic response of a bridge should include information on: (a) bridge geometry, including lengths, widths, overall heights, relative heights of various bents along the length of the bridge, and skew; (b) materials of construction; (c) member sizes, reinforcement, and detailing; (c) bearings, joints, and seat widths; (d) foundations and soil conditions; and (e) abutments. Although this information can be obtained from as-built drawings for individual bridges, this can be a laborious task when many bridges are involved (e.g., for SRA of a highway system). Furthermore, such data are usually not available in a computerized database that can be rapidly accessed for seismic evaluation of large numbers of bridges.

4.2.1.2 Current Databases and Bridge Management Systems

The only available nationwide computerized database for bridges is the National Bridge Inventory (NBI) database that is required by the National Bridge Inspection Standards established by the Federal Highway Administration. This database serves to facilitate inspection, to provide information for aggregation into a report to Congress on the number and state of the nation’s highway bridges, and to identify and classify the Strategic Highway Corridor Network and its connectors for defense purposes (FHWA 2003). The database has not been developed to provide information for evaluation of bridge performance during earthquakes or other natural or man-made hazards. Therefore, although the NBI database includes some relevant bridge attributes, it does not include sufficient data for detailed seismic vulnerability evaluation.

In addition to the NBI database, bridge management systems -- which include PONTIS (initiated by the FHWA) and BRIDGIT (initiated through the National Cooperative Highway Research Program) -- are being used by a number of states. These systems provide analytical methods that facilitate efficient and cost-effective allocation of resources for maintenance, repair, and upgrading of the nation’s highway bridges. They do not currently address seismic risk issues and, as a result, the data fields contained in these systems do not include most of the attributes that would be needed for seismic vulnerability assessment of a bridge. In recognition of this need, the feasibility of including seismic vulnerability evaluation in the PONTIS bridge management system has been assessed (Small 1997 and 1999).

4.2.1.3 Further Developments

4.2.1.3(a) California Department of Transportation Database

In some states whose highway systems have been subjected to damaging earthquakes, expanded bridge databases have been developed that supplement the data contained in the NBI database by providing additional bridge attributes that are relevant to seismic response. For example, the California Department of Transportation (Caltrans) is in the process of developing a supplementary database for bridges statewide. Some of the data fields that have been developed thus far are listed in Table 4-1 (Yashinsky 2005).

Table 4-1. Supplementary Bridge Database under Development at Caltrans

Type	Description
Relevant Dates	Dates of initial construction and any improvement (rebuilding, widening, etc.)
Seismic Retrofit	Whether bridge has undergone Phase 1 retrofit (joint restrainers) or Phase 2 retrofit (column jacketing), or whether it has been rebuilt.
Route Type	Whether bridge is along lifeline route (route critical to emergency response) and whether there are nearby detour routes.
Seismic Hazards	Design earthquake magnitude, distance to causative fault, and ground (rock) acceleration. Whether prone to damage from vertical acceleration, liquefaction, fault rupture, or tsunami, and whether on hanging wall of a dipping fault.
Superstructure	Number of spans, number of hinges, material of construction; Whether large skew angles, ,slab bridge with hinges, concrete bridge with restrainers.
Substructure	Whether substructure includes outriggers (including type of outrigger), flared columns (and whether flares are not retrofitted), pier walls,
Foundations	Types of piles, whether piles are battered, whether pile extensions, whether footings have top mat steel but no ties, whether footings are cantilevered and have long length-to-depth ratio
Joints/Seats	Whether joints have restrainers with threaded lock, grouted restrainers, short seat widths with no restrainers

Yashinsky 2005

4.2.1.3(b) Expanded Bridge Database for Shelby County, Tennessee (Jernigan 1998)

As part of his Ph.D. dissertation work, Jernigan (1998) performed research with the following objectives: (a) to develop structural attribute data for bridges in Shelby County that can be used in demonstration SRAs of the county's highway system; (b) to develop a framework for guiding the future development of structural attribute databases for SRA of highway systems nationwide; and (c) to provide data that can be used by state, county, and city government agencies for seismic risk evaluation and risk reduction planning. To accomplish this, Jernigan compiled extensive spatial and structural data from the NBI database, engineering drawings, inspection reports, and visual observations of 452 bridges and culverts in Shelby County. These data were incorporated into a GIS database developed at the Center for Earthquake Research and Information at the University of Memphis (see Table 4-2).

Table 4-2. Jernigan et al. (1998) Database for Bridges in Shelby County, Tennessee

File Number	Description	Structural Attributes
B-1	Relevant Information from NBI Database	Bridge ID number, route, location (log mile), feature crossed by bridge, maximum span length, total length, roadway width, bridge width, average daily traffic, year built, skew angle, superstructure types (main span and approach span), number of main spans, and number of approach spans.
B-2	Abutment Attributes	Bridge ID number, abutment type (material, type, and fixity), abutment bearing and expansion type, seat width, foundation type, and whether seismic retrofit was implemented.
B-3	Bent File No. 1	Bridge ID number, bent type and material, superstructure to substructure connectivity, bent bearing and expansion type, seat width, number of columns per bent, maximum column height, and minimum column height.
B-4	Bent File No. 2	Bridge ID number, column fixity (to bent cap and to pile cap or footing), column size (at top and bottom), column shape, vertical reinforcement, transverse reinforcement, and foundation type.

4.2.1.4 Bridge Database for REDARS™ 2

In view of the lack of other computerized bridge data, the REDARS™ 2 Import Wizard is using the NBI database as the source of bridge data for use in SRA applications (Appendix C). However, the limitations of the use of this database for seismic analysis applications are well known, and initial discussions among various researchers and transportation agencies have addressed the needed for expanding this database (TCW 2003 and 2005).

4.2.2 MODEL FOR ESTIMATING BRIDGE DAMAGE STATES DUE TO GROUND SHAKING

4.2.2.1 General Evaluation Procedure

REDARS™ 2 uses a default model for estimating bridge damage due to ground motions that corresponds to the HAZUS99-SR2 model (FEMA 2002). This model uses input-data fields extracted from the NBI database for bridges nationwide. Table 4-3 shows how data relevant to seismic performance evaluation were inferred from these NBI data. This model is summarized in the following subsections, and is further described in Section G.2 of Appendix G.

Table 4-3. Fields in NBI Database used in HAZUS99-SR2 Bridge Model to Infer Bridge Attributes Relevant to Seismic Performance

NBI Data Item	Definition	Skew Factor	3-D Response Factor	Use in Inferring Bridge Fragility
1	State		X	To infer seismic design code used.
8	Structure Number			General ID Number.
27	Year Built		X	Infer whether seismic or conventional design
34	Skew	X		
42	Service Type			To select highway bridges.
43	Structure Type		X	To infer which type of “standard” bridge to use as basis for fragility curve development.
45	Number of Spans in Main Unit		X	To infer whether single- or multiple-span bridge.
46	Number of Approach Spans			To infer if bridge is a major bridge (as defined in FEMA, 2002).
48	Length of Maximum Span		X	To also infer if bridge is a major bridge (as defined in FEMA, 2002)
49	Structure Length		X	To infer average span length. To compute replacement value.
52	Deck Width			To compute replacement value.

Mander and Basoz 1999

4.2.2.2 Damage States

Table 4-4 defines the qualitative damage state descriptors used by the HAZUS99-SR2 bridge model. Five different damage descriptors are used. These descriptors provide only partial information needed for the repair estimates that are subsequently discussed in Section 4.5.

4.2.2.3 Development of HAZUS99-SR2 Model

The HAZUS99-SR2 estimation of bridge damage states is based on development of an equivalent pushover capacity spectrum, use of this capacity spectrum along with the bridge attributes listed in Table 4-3 in order to develop spectral acceleration capacities for each damage state, and comparisons of the earthquake’s demand spectral acceleration to these various spectral acceleration capacities in order to obtain the bridge damage state.

Table 4-4. Damage States considered in HAZUS99-SR2 Bridge Model

Damage State Designation		Description
Number	Level	
1	None	First yield.
2	Slight	Minor cracking and spalling of the abutment, cracks in shear keys at abutment, minor spalling and cracking at hinges, minor spalling of column requiring no more than cosmetic repair, or minor cracking of deck.
3	Moderate	Any column experiencing moderate shear cracking and spalling (with columns still structurally sound), moderate movement of abutment (< 5.1 cm) (< 2 inches), extensive cracking and spalling of shear keys, connection with cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of approach.
4	Extensive	Any column degrading without collapse (e.g., shear failure) but with column structurally unsafe, significant residual movement of connections, major settlement of approach fills, vertical offset or shear key failure at abutments, or differential settlement.
5	Complete	Collapse of any column, or unseating of deck span leading to collapse of deck. Tilting of substructure due to foundation failure.

FEMA 2002

4.2.2.3(a) Pushover Capacity Spectrum

The pushover capacity spectrum is a plot of equivalent five percent damped spectral acceleration vs. spectral displacement (which is related to drift). Spectral displacements (drifts) that represent the onset of each damage state are also defined. In their original development of an early version of this HAZUS99-SR2 model, Mander and his colleagues established capacity spectra and drift limits for each damage state for each of each of six "standard" bridges, defined as long, un-skewed bridges that represent six different commonly occurring bridge types. Each capacity spectrum (which includes effects of strength degradation and hysteretic energy dissipation) was obtained as the sum of the capacity contributions of the piers and the three-dimensional arching action of the deck (Dutta and Mander, 1998; Mander and Basoz, 1999).

- ***Pier Contribution to Bridge Capacity.*** The strength capacity of a bridge pier will usually decay as the earthquake shaking proceeds. The magnitude and rate of this decay will depend on the design details at potential plastic hinge zones -- particularly connection details such as lap splices and anchorage zones -- and on the shear capacity of the columns and the column-to-cap connections. Although sophisticated energy-based procedures are available to evaluate these sources of strength decay, a simplified displacement-based analysis method is used here, to increase the speed of the evaluation. The method uses a simplified strength-degradation model for the bridge pier, where the total pier capacity consists of: (a) diagonal strut (or arch) action to represent the concrete resistance; and (b) resistance contributions of the longitudinal and transverse reinforcing steel. These contributions to the pier capacity are expressed in terms of geometric factors obtained or inferred from the NBI database.

- ***Deck Contribution to Bridge Capacity.*** The deck's contribution to the bridge's total base shear capacity has been systematically overlooked in most capacity analyses. This contribution is due to the resistance of the deck resulting from plastic moments that are mobilized by the bearings working as a group. This action occurs because, as the deck rotates, the resulting lateral displacements are resisted by frictional forces in each bearing and by arching action of the deck. These effects are evaluated for bridges with multiple simply-supported spans and with continuous spans, by using a plastic mechanism analysis to establish the deck capacity as the lowest capacity of all possible postulated failure mechanisms. These failure mechanisms depend on the geometry of the deck spans, the relative flexibility of the pier bents, and the resistance and capacities of the bearings.

4.2.2.3(b) Median Spectral Acceleration Capacity for each Damage State – Standard Bridges

With this capacity spectrum as a starting point, Mander et al. used the following steps to establish median acceleration capacities for each standard bridge type and each damage state:

- The capacity spectrum is overlaid onto a smoothed five percent damped spectrum shape, whose spectral accelerations at a period of 1.0 sec. and 0.3 sec. are assumed to be equal to the peak ground acceleration (PGA, or zero-period spectral acceleration) and 2.5 x PGA, respectively. This assumption is also a basis for the ground motion spectrum shape developed under the National Earthquake Hazard Reduction Program (NEHRP).

- This smoothed spectrum shape is scaled by alternative PGA values until it intersects the capacity spectrum at the drift (spectral displacement) level that corresponds to the onset of a given damage state. The PGA level at which this occurs is defined as the median PGA for the onset of the given damage state.

- Using the above relationships between spectral acceleration and PGA for the smoothed spectrum shape, the above median PGA capacities are converted to corresponding spectral acceleration capacities at periods of 1.0 sec. and 0.3 sec.

4.2.2.3(c) Median Acceleration Capacities for each Damage State – Actual Bridge

The acceleration capacities for each damage state at the actual bridge being evaluated are obtained by multiplying the corresponding acceleration capacities for the appropriate standard bridge (see Section 4.3.3.2) by factors that correct for the effects of skew and three-dimensional arching action of the actual bridge.

4.2.2.4 Modification of HAZUS99-SR2 Structural Capacities

During the development and testing of the REDARS™ 2 software, the software was used to predict bridge damage during the 1994 Northridge Earthquake, and these predictions were then compared to bridge damage observations after the earthquake. These comparisons showed that the HAZUS99-SR2 model substantially over-predicted the number of bridge collapses from the earthquake. This will have a particularly important effect on the REDARS™ 2 travel time estimates, since the default bridge repair model that is described in Section G.4 shows that by far, the most reductions in bridge traffic states occur when the bridge has collapsed.

For this reason, it was necessary to adjust the HAZUS99-SR2 model to improve these bridge collapse predictions. This adjustment consisted of determining a modification factor, named "α," that is applied to the HAZUS99-SR2 median bridge capacity, in which the bridge damage probability distribution was assumed to be lognormal with a standard deviation of 0.35. The process that was used to develop α is described in detail in Appendix K. It involved carrying out multiple sets of 4,000 simulations of bridge damage estimates for the Northridge Earthquake, in which uncertainties in the ground-motion estimates and the bridge damage predictions were considered. For each set of simulations, different α factors were assumed, and bridge damage throughout the northern Los Angeles area due to the Northridge Earthquake was estimated. Then, the average number of bridge collapses was estimated, and those bridges with the highest probability of collapse were identified in order to check whether these bridges corresponded to the bridges that actually collapsed during the Northridge Earthquake. In these analyses, retrofit enhancement factors developed by Shinozuka (2004) were used in the modeling of the relatively few bridges in the system that had been column jacketed at the time of the Northridge Earthquake.

These results for each different α factor were then compared to the Northridge Earthquake bridge damage observations. This comparison was the basis for selecting an α factor whose probabilistic predictions of bridge collapse (in terms of average number of collapses and locations of bridge collapses) were consistent with Northridge Earthquake observations.

In addition to determination of α factors for probabilistic SRA, the above process was repeated assuming median values of all uncertain parameters and carrying out deterministic estimates of bridge damage. The α factors for use in deterministic applications of REDARS™ 2 were thereby obtained. Results from the development of α factors for probabilistic and deterministic applications of REDARS™ 2 are provided in Appendix K.

It is noted that this adjustment of the HAZUS99-SR2 structural capacities was based on damage observations from one earthquake only. Additional investigations of bridge damage should be made for other earthquakes in the United States where bridge damage observations are well documented, and electronic databases of bridge attributes at the time of these earthquakes are available. Unfortunately, the Northridge Earthquake is the only known major earthquake that has occurred in the United States where these criteria are met.[3]

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[3] During this project, development of alpha factors based on calibrations against observed bridge damage during the 1989 Loma Prieta, California Earthquake was also attempted. However, it was found that data describing bridge attributes in the San Francisco Bay Area at the time of that earthquake were not available. This was important because the attributes of many of the Bay Area's bridges at the time of the earthquake (particularly for the bridges that were severely damaged during the earthquake) were very different than the current attributes of these bridges

4.2.2.5 Implementation of Modified HAZUS99-SR2 Model

The step-by-step procedure for applying the modified HAZUS99-SR2 bridge model in REDARS™ 2 is described in Appendix G. This procedure contains the following main steps for each earthquake scenario and simulation:

- *Demand Spectral Acceleration.* Use the models described in Section 3.3 to estimate the demand spectral acceleration at the site of the bridge.

- *Spectral Acceleration Capacity.* Use the procedures described in Section G.2. to estimate the spectral acceleration capacity for each damage state of the bridge. In this, include the structural capacity modification factors (α factors) listed in Table G-6 to obtain an adjusted capacity for each damage state.

- *Bridge Damage State.* Compare the demand spectral acceleration to the spectral acceleration capacity for each damage state, in order to identify the damage state of the bridge for this earthquake scenario and simulation.

4.2.3 MODEL FOR ESTIMATING BRIDGE DAMAGE STATES DUE TO GROUND DISPLACEMENT

In addition to ground shaking, bridges can be damaged by permanent ground displacement (PGD) from earthquake-induced liquefaction, landslide, or rupture of a fault located beneath the bridge. The REDARS™ 2 default model for estimating bridge damage states due to PGD is the simplified HAZUS99-SR2 model (FEMA 2002). This model only considers effects of PGD on incipient unseating and collapse, and on bearings. It does not consider the possibly significant effects of PGD on abutments and foundations (probably because bridge abutment and foundation attributes are not included in the NBI database). In this, it is noted that only limited research has been carried out to estimate potential bridge damage states due to PGD. Future research to develop improved models is recommended.

The main steps in applying the HAZUS99-SR2 model for estimation of bridge damage due to PGD are summarized below. The model is further described in Section G.3.

Step 1. Estimate Demand PGD

For a given earthquake scenario and simulation, use the procedures outlined in Section 3.4 or 3.5 to estimate the bridge's site-specific PGD due to liquefaction or fault rupture hazards.

Step 2. Develop PGD Capacity for "Standard" Bridge

The HAZUS99-SR2 model includes a table of PGD capacities that correspond to the onset of each damage state for various types of "standard" bridges as defined in Section 4.2.2.3(a). (This table is reproduced as Table G-8 in Section G.3). This table is used to obtain the PGD capacity for the standard bridge type that best corresponds to the actual bridge.

Step 3. Develop PGD Capacity for Actual Bridge

The above standard bridge PGD capacities are multiplied by a factor that depends of the actual bridge's length, width, skew angle, and number of spans, in order to obtain PGD capacities for each damage state that correspond to the actual bridge.

Step 4. Estimate Bridge Damage State

The demand PGD from Step 1 is compared to the actual bridge's PGD capacity for each damage state to estimate the bridge's damage state for this earthquake scenario and simulation.

4.2.4 BRIDGE REPAIR MODEL

After a bridge's damage state is estimated for a given earthquake scenario and simulation, the next step is to use an appropriate repair model to estimate how the damage will be repaired, how much the repairs will cost, how long they will take, and how traffic along the bridge will be affected during repair. As previously noted, these repair estimates will depend on the transportation department's experience and resources for post-earthquake bridge repair and on the construction, maintenance, and design practices for bridges within the region.

Because these factors will invariably differ from one region of the country to the next, it is not possible to provide a default repair model that applies to all regions. Instead, REDARS™ 2 provides a default model developed in close collaboration with senior bridge engineers from Caltrans. Because these models incorporate the extensive Caltrans experience in post-earthquake bridge repairs, they represent a reasonable starting point for establishing a REDARS™ 2 bridge repair model for other regions of the country. However, because of the factors listed in the previous paragraph, it will be necessary for REDARS™ 2 users from other states/regions to adjust/override this default repair model to better represent their particular operating conditions, repair resources, and construction practices.

The default bridge repair model developed in collaboration with Caltrans staff is described in detail in Section G.4. In this, bridge traffic states are provided as a percentage of the bridge's pre-earthquake traffic-carrying capacity for each of the HAZUS99-SR2 damage states listed in Table 4-3. For each damage state, these traffic capacities will vary with time after the earthquake in order to reflect estimated rates of repair. They also vary with the number of bridge spans. In this model, it is assumed that a bridge will be either fully closed or fully open at any time during the repairs; i.e., reopening of the bridge to partial traffic at any time prior to completion of repairs is not included in this model.

The default bridge repair model also includes repair cost estimates for each damage state. These are provided as repair cost ratios, which is the ratio of the repair cost for that damage state to the replacement cost. The replacement cost is estimated as the product of a unit replacement cost (assumed to be \$150/ft^2) and the bridge deck's surface area. These repair cost ratios and unit replacement costs can be overridden by the REDARS™ 2 user.

4.3 DEFAULT MODEL FOR APPROACH FILLS

If approach fills alongside bridge abutments have not been adequately compacted during construction, they are vulnerable to damage from earthquake-induced differential settlement. These differential settlements are often localized due to the rigidity of the abutment wall, and the difficulty in manipulating large compactors near walls. This increases their potential for damage. It is noted that approach-fill settlement was the most common type of highway-system damage due to the 1994 Northridge Earthquake.

The REDARS™ 2 default approach-fill model is described in detail in Section H.1 of Appendix H and is briefly summarized here. It contains two main parts: (a) estimation of approach fill settlement; and (b) estimation of corresponding damage states, repair costs, and traffic states.

4.3.1 APPROACH FILL SETTLEMENT

The REDARS™ 2 approach for estimating earthquake-induced settlement of bridge approach fills is based on the Youd (2002) model for dry soils. The settlement is computed separately for each earthquake scenario and simulation, once the magnitude and location of the earthquake are specified and the level of ground shaking is estimated throughout the highway system.

The Youd (2002) model for estimating approach fill settlement (Section H.1.1) requires input data that characterizes the bridge (bridge number and location, relative compaction of approach-fill soils, and maximum thickness of the soils) and the earthquake scenario/simulation (the earthquake's moment magnitude and the bridge's peak ground acceleration). These data are used in a table developed by Youd that estimates volumetric strain (percent) for loose, moderately-dense, and dense fills as a function of: (a) moment magnitude; and (b) for each moment magnitude, the peak ground acceleration. After the volumetric strain is obtained from this table, it is multiplied by the approach-fill thickness to estimate the earthquake-induced settlement.

The REDARS™ 2 model uses a default approach-fill thickness of 12 ft and a default relative compaction of 95 percent. In addition, the following algorithm is used in REDARS™ 2 to estimate a default number of approach fills for each bridge (which can be overridden by the user):

- If the REDARS™ 2 bridge model shows the bridge location to be on a link with no other bridges nearby, the bridge is assumed to have two approach fills -- one at each end of the bridge.

- The NBI database often represents an elevated viaduct of extended length as a series of very closely spaced bridges. Therefore, an individual bridge within this series that is immediately adjacent to another bridge on each side is considered to be within the elevated viaduct and therefore is assumed to have no abutments, and no approach fills. An individual bridge that is located at one end of this series of bridges is considered to represent the start/end of the elevated viaduct. Therefore, it is assumed to have one abutment and one approach fill.

4.3.2 REPAIR MODEL

As for the bridges, the default model for repair of earthquake damage to approach fills was developed in close collaboration with senior members of Caltrans' engineering/maintenance staff who have extensive experience in approach-fill design, construction, maintenance, and repair. Therefore, it is directly applicable to repair of approach fills in California only. REDARS™ 2 users from other regions of the country whose approach-fill configurations, soil conditions, and maintenance, design, construction, and repair practices differ from those in California should override these default repair estimates.

The REDARS™ 2 default repair model is described in detail in Section H.1.2 and is briefly summarized here. It defines three ranges of approach-fill settlement that will entail different levels and types of repair. For each range, the model prescribes the approach fill's traffic state at various times after the earthquake as well as its repair cost (expressed as a percentage of the replacement cost). In this, a default replacement cost of $14,500/lane is assumed. These default traffic states, repair costs, and replacement cost can be overridden by the user.

4.4 DEFAULT MODEL FOR ROADWAY PAVEMENTS

Flexible or rigid roadway pavements are susceptible to damage/closure due to earthquake-induced ground displacement hazards. These hazards include differential settlement of dry or moist soils, lateral spreading and settlement of liquefiable soils, sliding of embankments or slopes due to instability of embankments or underlying soil materials, and surface fault rupture.

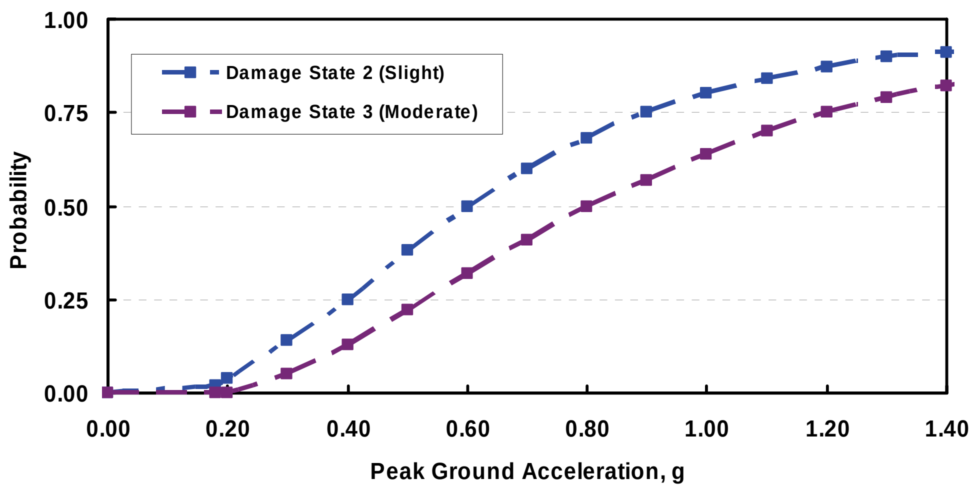
The default model for roadway pavements is described in detail in Section H.2 and is briefly summarized here. The process for developing the model and the form of the model are similar to those summarized above for approach fills. As with the approach fill model, the roadway pavement model takes the form of a table that, for different ranges of earthquake induced PGD, provides default repair procedures and associated traffic states at various times after the earthquake as well as repair costs per lane mile.

This roadway-pavement model was developed in close collaboration with Caltrans' senior staff members who have extensive experience in pavement design, construction, maintenance, and repair. Therefore, the model is directly applicable to roadway pavements in California only. REDARS™ 2 users from other regions of the country should override the model as needed to more appropriately represent roadway-pavement practices in their region.

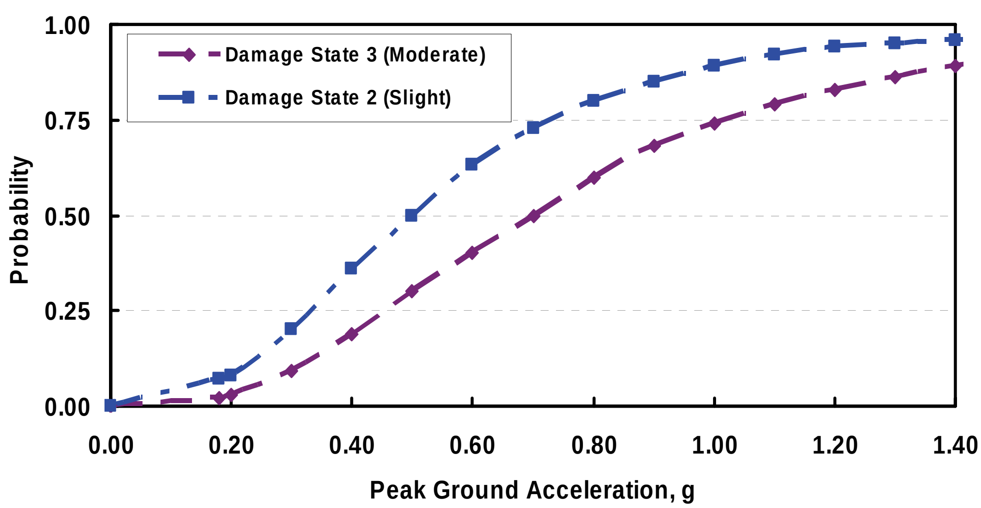
4.5 TUNNEL MODELS

The seismic performance of tunnel structures will depend on many factors such as: (a) whether they are constructed as drilled or cut-and-cover structures; (b) their length, cross section, depth below the ground surface, and materials of construction; and (c) the characteristics of the surrounding subsurface soil or rock materials in the vicinity of the tunnel, including their material properties, layering, and susceptibility to major ground movement due to liquefaction or fault rupture. In view of this, and also because the tunnels are often important to the seismic performance of the overall highway system, it was decided that such structures can best be represented by user-specified fragility models that are based on special analysis of these key facilities, rather than by default models.

However, if no such analysis results are available or if time and budget constraints preclude the development of such results for REDARS™ 2 applications, the user can fall back on existing fragility models that have been developed for broad classes of tunnel structures. For example, HAZUS99-SR2 models that may be implemented as user-specified models under these circumstances are shown in Figures 4-1 and 4-2. An example repair model that was recently developed for a drilled tunnel in California is shown in Table 4-5.



a) Drilled Tunnels



b) Cut-and-Cover Tunnels

Figure 4-1. HAZUS99-SR2 Tunnel Fragility Models: Ground Shaking (FEMA 2002)

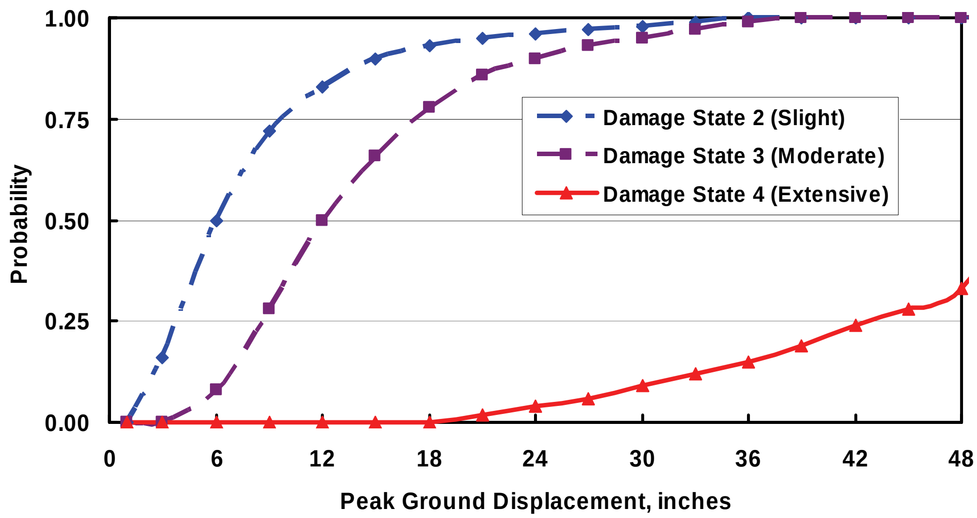


Figure 4-2. HAZUS99-SR2 Tunnel Fragility Models: Permanent Ground Displacement (NIBS 2002)

Table 4-5. Example Repair Model for Drilled Tunnel in California[1,2]

Damage State[3]		Seismic Hazard that can Cause this Damage State	Traffic State		Repair Cost (percent of Replacement Cost)[5]
No.	Description		Days after EQ[4]	Percentage of Pre-EQ Lanes Available	
2	*Slight.* Minor cracking of tunnel liner (requiring only cosmetic repair). Some rock falling or slight ground settlement at tunnel portal.	Ground Shaking (GS) or Permanent Ground Displacement (PGD)	0 days	0%	10%
			4 days	100%	
3	*Moderate*. Moderate structural cracking of tunnel liner and/or moderate rock falling	GS or PGD	0 days	0%	25%
			11 days	100%	
4	*Major.* Major structural cracking of tunnel liner and/or major settlement at tunnel portal	PGD only	0 days	0%	75%
			30 days	100%	

Assumptions:

1. Tunnel is about 4,000 ft-long and each bore contains two 12-ft lanes.
2. Tunnel is located along designated lifeline route (i.e., route must remain open to emergency vehicles after an earthquake). Therefore, repair materials, equipment, and crews will be rapidly mobilized to repair the tunnel after an earthquake.
3. Various damage states extend through up to half of the length of the tunnel bores.
4. Downtimes = times needed to reopen tunnel to traffic. It includes time for mobilization of repair/construction resources to tunnel site. Times to complete repair may extend beyond above downtimes; i.e., it is assumed that repairs can be completed after tunnel is reopened to traffic (by construction crews working during off hours, etc.).
5. Replacement cost = \$75/ (ft^2 of area), where area = damaged length along tunnel x width of roadway with two 12-ft lanes.

CHAPTER 5: SYSTEM MODULE

5.1 OVERVIEW

The first SRA applications using a forerunner of the current REDARS™ 2 software (termed REDARS™ beta) used a network-analysis process that was based on the following assumptions:

- ***User-Equilibrium Model.*** For a given trip, a user will choose a route between an origin and destination that will minimize the travel time required for that trip.

- ***Fixed Trip Demands.*** The conventional user-equilibrium model assumes that the network's post-earthquake trip demand is equal to the pre-earthquake trip demand. Under these conditions, even though earthquake-induced damage may result in road closures and a corresponding increase in traffic congestion, the trip demand on the highway-roadway system would not be affected by this increased congestion.

- ***One Trip Type.*** All traffic is represented by a single OD matrix, and every trip is represented by the same economic value whether it is taken by car or truck.

- ***Moore-Pape Minimum-Path Algorithm.*** Route choice in accordance with the above user-equilibrium model is estimated by the Moore-Pape algorithm, which attributes nodes according to the travel time from an origin (Moore 1957; Pape 1974).

The REDARS™ 2 network-analysis procedure has been significantly improved. These improvements are listed below and are summarized in the remainder of this chapter.

- ***Variable-Trip Demands.*** The user-equilibrium model with fixed trip demand has been replaced by a variable-demand model that accounts for the effects of traffic congestion.

- ***Dual-Simplex Minimum-Path Algorithm.*** The Moore-Pape algorithm has been replaced by the less computationally intensive dual-simplex algorithm, detailed by Florian et al. (1981).

- ***Multiple Trip Types.*** REDARS™ 2 enables users to define multiple types of trips to be carried by the highway-roadway system and to input separate trip tables and economic loss calculation parameters for each different trip type.

5.2 VARIABLE-DEMAND MODEL

5.2.1 STATEMENT OF THE PROBLEM

The user-equilibrium model with fixed trip demands that was included in the beta version of REDARS™, is widely used in transportation network analysis. However, initial results from a recent validation of this model against observed traffic flows after the Northridge Earthquake indicate that, although the model is adequate for region-wide modeling of traffic flows, it does not provide adequate estimates of traffic along specific highways or links (App. I). For example, according to local traffic reports obtained one day after the earthquake (Caltrans 1995), observed traffic volumes doubled on roads near collapsed bridge sites (i.e., near the bridge collapses at I-10/La Cienega, SR-118/Gothic, and I-5/SR-14). Under these conditions, the observed travel-times along these roads increased by only 15 minutes per trip relative to pre-earthquake travel times. However, when the user-equilibrium model with fixed trip demand was used to predict post-earthquake travel time along these same roads, the model over-estimated travel time by as much as a factor of 10.

One reason for this result is that this model assumes inelastic (i.e., fixed) trip demands. However, this assumption is not plausible under conditions of substantially reduced network capacity and corresponding increased traffic congestion. Under this situation, observed data has shown that many travelers are unwilling to endure such travel time delays and will instead forego their trip. To account for this, major efforts under this project have focused on the development of a variable-demand model (VDM) for network analysis that replaces the fixed-demand model (FDM). This model is summarized below, and is further described in Section I.1 of Appendix I.

5.2.2 MODELING ISSUES

Implementation of the VDM in REDARS™ 2 was complicated by the two issues listed below. Section 5.2.3 describes how these modeling issues have been addressed.

- The VDM presumes that less network traffic capacity will reduce trip demand and increase travel times. However, in an actual highway-roadway system, the available capacity for some zone-pairs may actually increase after an earthquake due to unique rerouting conditions.

- Initial VDM results indicate that the predicted equilibrium for zone-to-zone travel times will not always fall on the demand curve. Therefore, to address this complication, REDARS™ uses a rules-based approach to address zone-pair demand on a case-by-case basis.

5.2.3 MODEL DEVELOPMENT

This section summarizes the REDARS™ methodology for calculating the social cost of earthquake-induced traffic disruption using: a) zone-to-zone trip demands; and b) the corresponding change in travel time estimated by the VDM. Social cost includes the value of time due to increased traveler time on the roadway and the value of trips foregone.

As noted above, the FDM assumes that trip demand associated with zone-to-zone travel is inelastic; i.e., it does not vary with travel time. Under these conditions, all drivers continue to attempt travel, even if a trip takes several hours and has an unreasonable social cost. Figure 5-1 illustrates the social cost of a hypothetical earthquake under this situation. If the traffic-carrying capacity is reduced due to earthquake damage, the congestion will increase. The network capacity (or supply) is reduced from S_1 to S_2, and the fixed trip demand is represented by D_1.[4] The corresponding travel costs are P_1 and P_2 respectively, and the social cost is $(P_2 - P_1) * D_1$.

[4] Note that, in Figure 5-1, the axes are reversed for consistency with subsequent examples.

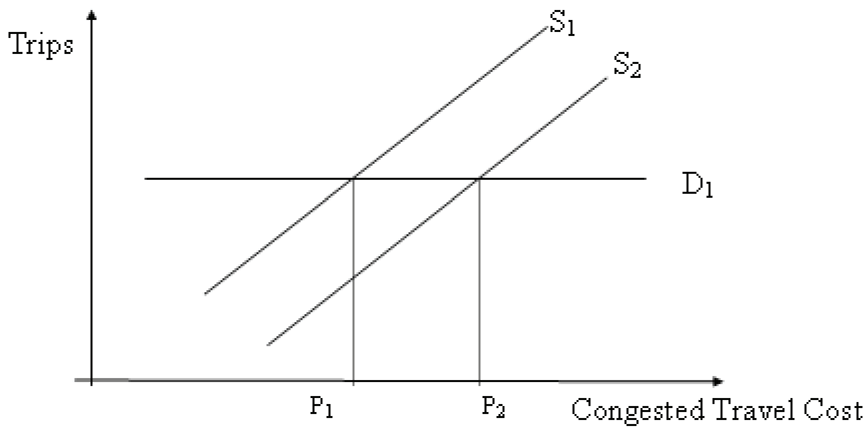


Figure 5-1. Fixed Demand Model for an Earthquake-Damaged Network

The assumption that travel demand remains constant is not appropriate for the analysis of a highway network where traffic-carrying capacity is drastically changing. Under these conditions, many drivers would be unwilling to endure very large increases in travel time, and would instead forego the trip or change their mode of travel. Thus, travel demand would be elastic; i.e., the travel time for trips taken would depend on the available capacity.

Figure 5-2 illustrates the resulting effects of elastic trip demand, as characterized by the VDM. This figure shows that before an earthquake, the highway system would provide a capacity of S_1, and the travel demand (D_1) on this network would result in an equilibrium travel time of P_1. After an earthquake, the capacity would be reduced to S_2, and the travel demand D_2 would results in a travel time of P_2'. The resulting social cost of this reduction in network capacity is given by the expression $[(P_2'-P_1)*D_2]+[(P_2'-P_1)*(D_1-D_2)/2]$, and will be much lower than the cost predicted by the FDM.

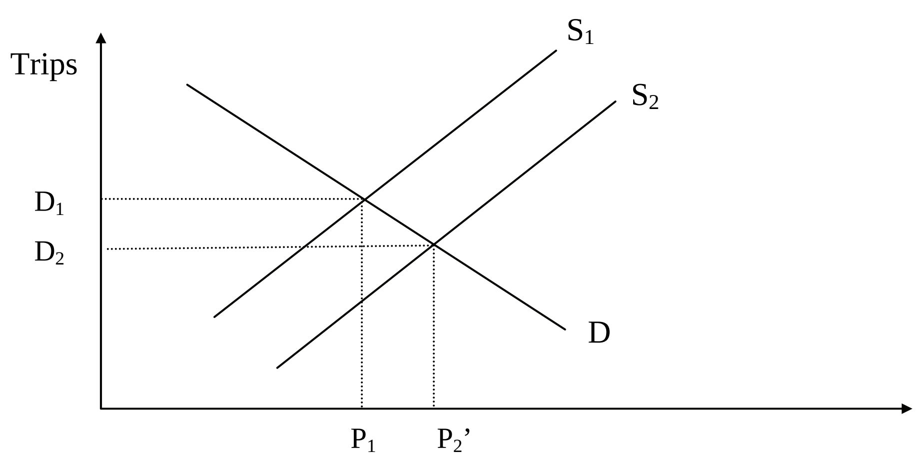


Figure 5-2. Variable-Demand Model for an Earthquake-Damaged Network

5.2.4 LOSS ESTIMATION CHALLENGES

Use of the VDM to estimate economic losses due to a reduction in network capacity presents several computational challenges. For example, the slope of the aggregate trip-demand curve must be estimated from minimal information. This process is discussed in this section, and its specific functional forms are provided in Section I.4 of Appendix I.

The mathematical form to the model is as follows:

$$\min\ z(\mathbf{x},\mathbf{q}) = \sum_a \int_0^{x_a} t_a(w)\ \ dw - \sum_{rs} \int_0^{q_{rs}} D_{rs}^{-1}(w)\ \ dw \qquad (5\text{-}1)$$

subject to

$$\sum_k f_k^{rs} = q_{rs} \qquad \forall r,s \qquad (5\text{-}2)$$

$$f_k^{rs} \geq 0 \qquad \forall k,\ r,s \qquad (5\text{-}3)$$

$$q_{rs} \geq 0 \qquad \forall r,s \qquad (5\text{-}4)$$

$$q_{rs} = D_{rs}\left(u_{rs}\right) \qquad \forall r,s \qquad (5\text{-}5)$$

$$x_a = \sum_{rs}\sum_k f_k^{rs} \cdot \delta_{a,k}^{rs} \qquad \forall a \qquad (5\text{-}6)$$

where

- t_a : link performance function of link *a*.
- D : demand function.
- D^{-1}: inverse of demand function.
- f_k^{rs} : flow on path *k* connecting OD pair *r*-*s*.
- q_{rs}: trip rate between OD pair *r*-*s*.
- u_{rs}: travel time between OD pair *r*-*s*.
- x_a : flow on link *a*.
- $\delta_{a,k}^{rs}$: = 1 if link *a* is on path *k* between OD pair *r*-*s*, otherwise = 0.

For some origin-destination zones with a minimal number of trips, the demand curve for specific zone-pairs may not match the elasticity and demand over time parameters established for the entire data set; therefore, the demand curve must be adjusted. In REDARS™ 2, individual zone-pairs with problematic results are identified and adjusted through a series of rules-based statements. The VDM adjusts trips and travel time by a constant value in each iteration. Each iteration seeks the optimal total travel time and the travel time associated with trip generation that minimizes the object function value given by Equation 5-1. In practice, the solution to this equation is dominated by zone-pairs with heavier demand in the first few iterations. For zone-pairs with light demand, VDM can not guarantee the equilibrium conditions. The details of these parameters are explained in Section I.4 of Appendix I.

There are additional cases where the VDM conditions are not solvable, due to a conflict with the demand curve. However, the demand curve is not established from survey data, and it cannot be assumed that the curve characterizes the actual activity system. Some possible relationships between pre- and post-earthquake trips, travel times, and demand where the VDM is not solvable are listed below, along with a description of how each relationship is handled in REDARS™ 2.

d_1 : Pre-earthquake trips
d_2 : Post-earthquake trips
t_1 : Pre-earthquake travel time
t_2 : Post-earthquake travel time
D : Demand function
C_1 : Additional travel time spent by drivers remaining in the system
C_2 : The value of forgone trips

***Case 1*: $d_1 = D(t_1)$, $d_2 = D(t_2)$, $d_1 > d_2$, and $t_1 < t_2$**

In this case, the earthquake reduces trip demand and causes higher travel time. This is the expected behavior, and occurred in more than 95 percent of all trips. If a zone is isolated from the network, d_2=0, and $t_2 = \infty$. In this case the earthquake calculations are as follows.

$$C_1 = d_2 \cdot (t_2 - t_1) \tag{5-7}$$

$$C_2 = \int_{t_1}^{t_2} D(w)\, dw \quad - C_1 \tag{5-8}$$

***Case 2*: $d_1 = D(t_1)$, $d_2 = D(t_2)$, $d_1 < d_2$, and $t_1 > t_2$**

This suggests that traffic conditions are improved by earthquake damage. This situation is unlikely. REDARS™ 2 assumes $d_1 = d_2$, and $t_1 = t_2$.

***Case 3*: $d_1 \neq D(t_1)$ and/or $d_2 \neq D(t_2)$**

Where the global solution from the VDM does not correspond to the given input demand function, the demand curve is shifted so that $d_1 = D(t_1)$ or $d_2 = D(t_2)$. Then, Equations 5-7 and 5-8 are applied.

When drivers forego travel, they can pursue other activities. The value of these forgone trips depends on differences between pre- and post-earthquake travel times and number of trips.

5.2.5 CALIBRATING THE DEMAND FUNCTION

A demand function should include origin-destination-specific parameters that reflect population size, income distribution, and vehicle ownership by origin zone, as well as employment statistics and retail-activity variables by destination zone. However, the only parameter in the demand function between origin-destination-zone pairs, is the travel time between zones. Therefore, the demand function must be calibrated against the estimated travel time. This calibration is summarized below.

In the VDM, a demand function must reflect a decrease in the percentage of trips as the travel time between zone-pairs increases. As travel time increases, trip rate decreases. In reality, however, the distribution of trip-rate as a function of travel time shows that the trip rate is largest at a certain travel time not equal to 0 (an anomaly of the model is an infinite demand calculate at T=0). For example, in the SRA of the Shelby County, Tennessee highway system that is described in Werner et al. (2000), this peak was estimated to be about 8 minutes. Although the actual trip rate is not a monotonic function of travel time, the VDM assumes that the relationship between trip rate and travel time follows the simple form shown in Figure 5-3. Based on this assumption, the demand curve is calibrated through a statistical regression between the trip rate and travel time. This process is included in the REDARS™ 2 Import Wizard.

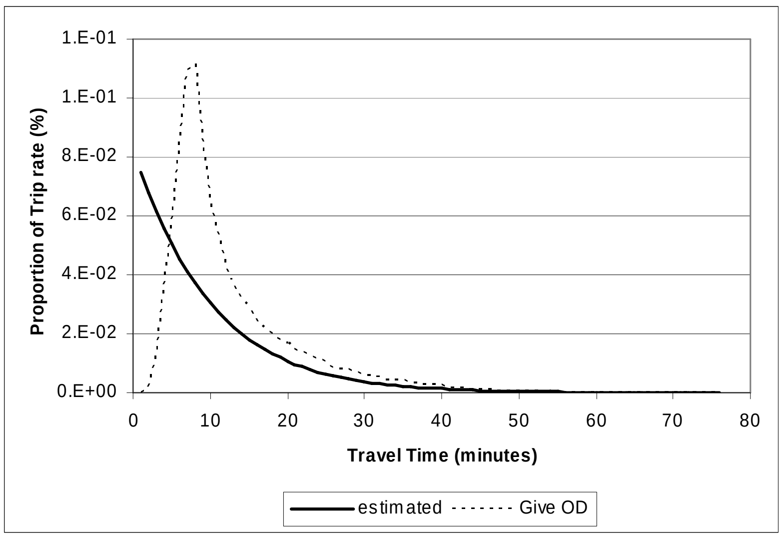


Figure 5-3. Real Trip Rate and Estimated Demand Function

5.2.6 PERFORMANCE OF VARIABLE-DEMAND MODEL

The VDM adjusts the trip rate according to the difference in level-of-service or increment of travel time. Figure 5-4 shows that most of the reduction in trip rate occurs for travel-time increases in the range of 10 ~30 minutes; and that this reduction tends to even out as the travel time increases beyond this range. This shows that the absolute value of the travel time is not directly associated with trip rate reduction. However, as shown in Figure 5-5, the reduction rate of travel demand has negative correlation to the rate of travel time. Travel times range from 0.85 to more than 2 times the baseline travel time. Over this range, more demand is reduced as travel time increases. For example, Figure 5-5, shows that when the travel time increases by 20-percent, the trip rate is about 80-percent of the baseline value. From this it can be concluded that the VDM is working as expected for cases where travel time is increased by a factor of ≤ 2 due to earthquake damage to the highway-roadway system.

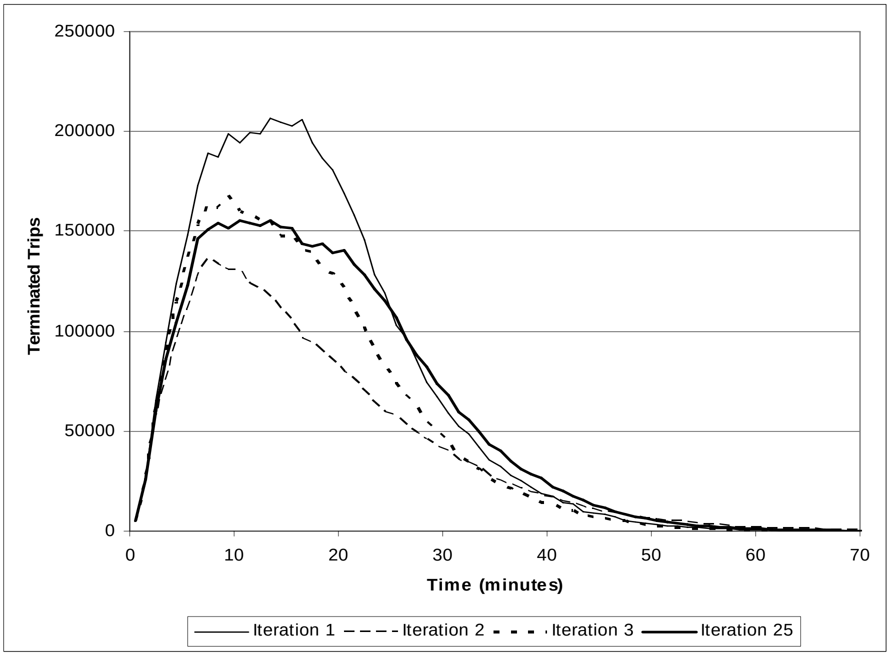


Figure 5-4. Trip Demand and Travel Time

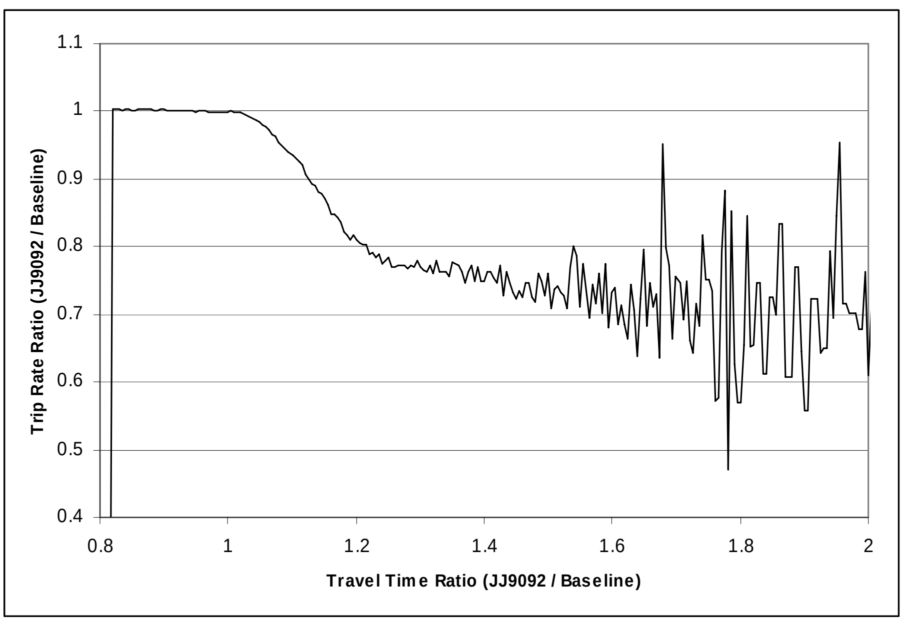


Figure 5-5. Reduced Trips and Travel Time

Results from REDARS™ 2 indicate that the VDM accounts for a reduction in trip rate and an increase in travel time according to the post-earthquake changes in network capacity. Analyzing the economic impact of an earthquake must consider the difference in system cost calculated by congestion. The difference in trip rate must be considered as another type of social cost, along with the value of foregone trips. REDARS™ 2 results using the VDM show that the model is useful for evaluating trip reduction as travel time increases. This indicates that the VDM is more appropriate for estimating post-earthquake traffic congestion than is the FDM.

5.3 UPDATE OF MINIMUM-PATH ALGORITHM

5.3.1 BACKGROUND

The network analysis procedure that was incorporated into the prior version of REDARS™ (see Werner et al., 2000) used the Moore-Pape minimum-path algorithm, which is an improved version of a label-correcting algorithm by Sheffi (1985). This algorithm establishes the path from a single "root" transportation zone to all zones in the system, and assigns travel demand from this zone to all other zones along the established path. The model repeats this process for all zones.

The efficiency of this model was increased through the discovery that two paths built from two adjacent root zones often share common links (Florian et. al., 1981). Through complex data structures implemented in the Dual-Simplex algorithm, the path information from one root is reusable for adjacent zones. Recycling the path information reduces computer running times significantly. In REDARS™ 2, run times for analyses that use this Dual-Simplex algorithm have been found to be about 30-percent lower than run times for the same analysis using the Moore-Pape algorithm. See Appendix I.6 for reduction rates for various size network configurations.

This section describes the minimum-path algorithm that recycles path information which, in REDARS™ 2, leads to reduced network-analysis run times. The role of the minimum-path algorithm in network analysis is summarized, and the more efficient Dual-Simplex algorithm, is described. In addition, the internal-memory structure of the network is included, and comparisons of results from the Moore-Pape and Dual-Simplex algorithms are cited.

5.3.2 MOORE-PAPE MINIMUM-PATH ALGORITHM

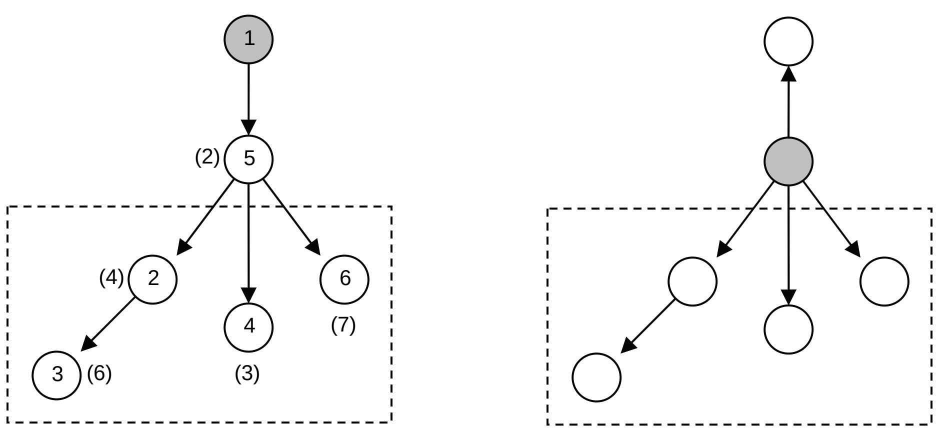
Previous versions of REDARS™ used the Moore-Pape path search algorithm adapted for transportation networks. This algorithm is particularly effective in cases where the number of nodes is much less than number of links, such as in power or communication networks. A communications switching-station, for example, typically manages thousands of telephone lines. When the number of nodes outnumbers the number of links, finding nodes on a path is more efficient than tracing links.

The Moore-Pape algorithm attributes nodes according to travel time from an origin. The transportation network analysis procedure repeats the algorithm iteratively in order to identify paths from all origins to all destinations in the network. After each path is calculated, the specific path, defined by a series of links, is discarded.

5.3.3 DUAL-SIMPLEX MINIMUM-PATH ALGORITHM

This process of discarding a minimum path after a calculation, as described above, is valid, since the minimum path from each origin is mathematically independent of that from other origins. However, independence does not imply that minimum paths from distinct origins do not share collections of links in a particular sequence. For example, in an urban transportation network, freeways accommodate a significant percentage of vehicle trips. For these networks, trips usually require shorter travel times when using freeways rather than local roads, and the proportional congestion due to the additional vehicles that use the freeway is less than that of local streets. Therefore, freeways are typically included in the minimum path between multiple zone-pairs, which indicates that a collection of links can be included in many travel paths.

Figure 5-6 illustrates how a collection of links can be shared by neighboring nodes. For example, the minimum path from Node 5 is seen to share many of the links included in the path to that node from Node 1. Links within the dashed box are common in paths from Node 1 to Node 5. For this situation, the minimum-path information, and the travel time to each node through the minimum path attained in a previous iteration of the algorithm may be reusable, which would reduce the overall network-analysis run times. The numbers in parenthesis in Figure 5-6 indicate travel time to reach the node from origin. The Dual-Simplex algorithm recycles the collection of links that are calculated in each iteration. When a set of links defines the shortest path between two nodes calculated in a previous iteration, these values are taken from these prior iterations, and are not recalculated. Section I.6 of Appendix I provides results from a simple test, which reveals that, use of the Dual-Simplex algorithm within REDARS™ 2 leads to computer-run times that are lower than run-times from the Moore-Pape algorithm, by factors ranging from 24-percent to 57-percent, depending on network redundancy.



(a) Path from Root-Node 1 **(b) Path from Root-Node 5**

Figure 5-6. Comparison of Minimum Paths from Neighboring Origins

5.4 MULTIPLE TRIP TYPES

Prior versions of REDARS™ used a single origin-destination trip table and set of economic loss parameters for computing losses due to travel-time delays. However, a highway-roadway system will invariably accommodate many different types of trips (e.g., automobile trips and various types of freight trips). In addition, these various types of trips will often have different origins and destinations within the region served by the highway-roadway system. Furthermore, these various types of trips will have different economic values.

In recognition of this, REDARS™ 2 now can consider any number of different types of trips. For each trip type, REDARS™ 2 enables users to input separate origin-destination trip tables that would reflect the uniqueness of its region-wide travel patterns.

This new feature of REDARS™ 2 also enables users to estimate separate economic losses for each trip type, and then aggregate the losses from all of the trip types in order to estimate total region-wide economic losses due to earthquake damage to a highway-roadway system. The process used in REDARS™ 2 for estimating these separate losses for each trip type consists of the following steps:

- ***Losses due to Travel-Time Delays***. Chapter 6, describes how, for different post-earthquake times, REDARS™ 2 estimates the total loss per day as the product of an economic-loss factor and the travel-time delays incurred at those times. As noted above, prior versions of REDARS™ accommodated only one economic-loss factor for all trip type, and multiplied that factor by a single set of system-wide travel-time delays, also for all trip types, in order to estimate a loss per day at each user-specified post-earthquake time. However, for each trip type, REDARS™ 2 now enables users to input different economic-loss factors for each trip type. In addition, REDARS™ 2 now separately tracks the travel-time delays for each trip and then uses these results to estimate separate overall system-wide travel-time delays for each trip type at each post-earthquake time. From this, for each separate trip type, the loss per day at a given post-earthquake time is computed as the product of the economic loss factor and the system-wide travel-time delay for that trip type. These loss results for each trip type can, of course, be summed over all trip types to obtain an aggregated total economic loss due to earthquake damage to the highway-roadway system.

- ***Losses due to Trips Foregone.*** As noted earlier in this chapter, the variable-demand model enables REDARS™ 2 to estimate economic losses from trips foregone due to increased traffic congestion caused by earthquake damage to the highway-roadway system. With the addition of this new capability for considering multiple trip types, REDARS™ 2 can now: (a) separately track each pre-earthquake trip for each trip type, along with its pre-earthquake travel time; (b) separately track each post-earthquake trip for each trip type at each post-earthquake time; (c) compare the pre-earthquake trips to the post-earthquake trips for each trip type, and thereby identify those trips not taken for each trip type at each post-earthquake time; and (d) from this, estimate the total losses due to trips foregone for each trip type, as described earlier in this chapter.

CHAPTER 6: ECONOMIC MODULE

6.1 BACKGROUND

One set of important end results from SRA of highway systems is the estimation of economic impacts of earthquake damage to the system. These effects can be conceptualized by considering that, in addition to damaging the highway system, earthquakes can also damage buildings, contents, and lifeline infrastructure. Building, content, and infrastructure damage will reduce the region's industrial capacity to produce goods and services. This will affect the traffic demands placed on the highway system after the earthquake. At the same time, the highway system damage will reduce the system's capacity to transport materials, equipment, employees, and other personnel essential to the productivity of firms and households in the region.

These factors together will affect the stricken region's economic productivity and capacity. Estimation of these effects requires the coupling of system, hazards, and component models, with regional economic models, which is a formidable task. Although progress has been made in this area (e.g., Cho et al. 2001; Shinozuka 2004), this is still an area of extensive research and development. This is because most regional economic models are aspatial. These models may treat interactions between economic sectors in considerable detail, but not in a spatially dis-aggregate way. Spatial dis-aggregation is needed to make the link between economic performance and access to lifeline services, including transportation. Furthermore, since access to transportation facilities is un-priced, the value of transportation services is not adequately represented in most regional economic models. Even if a spatially dis-aggregate model of the regional economy is available, it is still necessary to model economic responses to highway-system damage. These responses include changes in the propensity to travel, choice of destination, and choice of route.

Another important factor when using economic loss results for decision-making is evaluation of impacts of the highway-system damage on stakeholders. Future development of economic models should include assessment of who gains (e.g., construction industry) and who loses (e.g., business sectors heavily dependent on trucking to distribute goods) in the event of such damage.

6.2 OBJECTIVE

The objective of the Economic Module is to provide the input data and models necessary to estimate economic losses due to highway-system damage. REDARS™ 2 considers the following sources of economic loss: (a) repair costs; (b) losses due to earthquake-induced travel-time delays; and (c) losses from trips foregone due to earthquake-induced increases in traffic congestion. Section 6.3 summarizes the general approach used in REDARS™ 2 to develop default estimates of these loss sources, and Section 6.4 further discusses each of the sources. . The estimation of unit losses for calculating economic losses due to travel-time delays and trips foregone is discussed in Section 6.5.

6.3 GENERAL APPROACH FOR DEVELOPING DEFAULT LOSS ESTIMATES

REDARS™ 2 provides default parameters for estimating repair costs and losses due to travel-time delays and trips foregone. Any of these default parameters can be overridden by the REDARS™ 2 user.

REDARS™ 2 default repair-model parameters for bridges and for approach fills and roadway parameters are described in Appendices G and H respectively. These parameters are based on construction practices, repair resources (i.e., materials, equipment, and labor), and earthquake-repair experience in California. Their selection as the REDARS™ 2 default repair model was motivated by the extensive post-earthquake repair experience of the California Department of Transportation, which was viewed as a reasonable starting point for developing repair models for highway systems in other parts of the country. Of course, since construction procedures and repair resources and experience will differ from region to region, REDARS™ 2 users from other regions should override the current default repair-model parameters as needed to best represent repair procedures, resources, and experience for their particular region.

6.4 LOSS SOURCES

6.4.1 Repair Costs

REDARS™ 2 expresses default repair costs as percentages of the estimated total replacement cost for the component. These percentages will depend on the component's earthquake-induced damage state. The replacement cost is computed as the product of a unit cost and an effective area of the component. The effective area, in turn, is represented as the product of the component's length and its effective width, which will depend on the component type.

6.4.2 LOSSES DUE TO TRAVEL-TIME DELAYS AND TRIPS FOREGONE

The REDARS™ 2 variable-demand network-analysis procedure that is described in Chapter 5 represents how increased traffic congestion due to earthquake damage affects travel times throughout the system as well as trip demands on the system. That is, it accounts for possible increases in travel times and reductions in trip demands relative to the pre-earthquake conditions, as the level of traffic congestion increases. It also recognizes that different types of trips throughout the system (i.e., automobile trips and various types of freight trips) will have different economic values, and therefore estimates separate travel-time delays and trips foregone for each trip type. These new features are significant extensions of the prior network analysis procedure used in the initial version of REDARS™ 2 that is described in Werner et al. (2000). In that procedure, post-earthquake trip demands were assumed to be equal to pre-earthquake demands, and no distinction was made between different types of trips.

Figure 6-1, which is identical to Figure 5-2 shows how these losses are computed. In this figure, the highway system's pre-earthquake traffic-carrying capacity is represented by the parameter S_1, and the corresponding system-wide travel times and trip demands are represented by the parameters P_1, and D_1 respectively. After the earthquake occurs, the system's traffic carrying capacity reduces to S_2, its travel times increase to P_2', and its trip demands reduce to D_2.

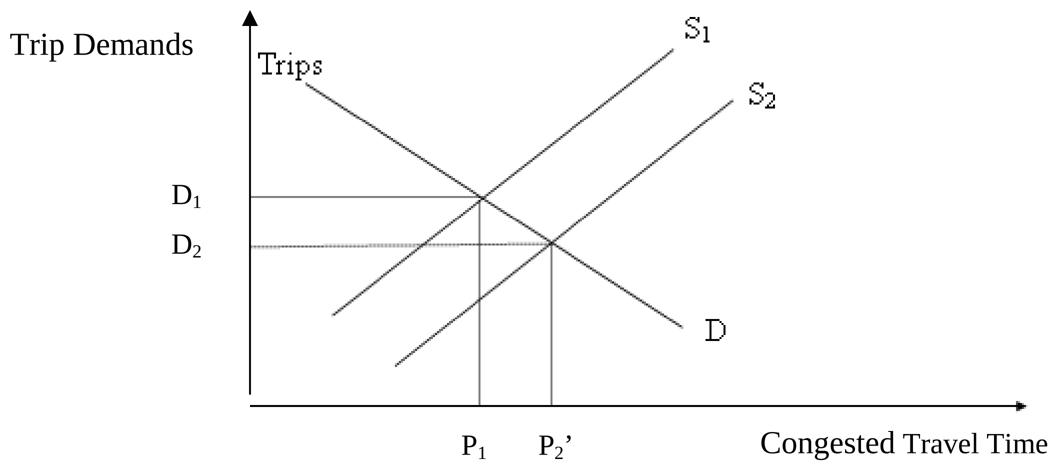


Figure 6-1. Variable-Demand Model for Earthquake-Damaged Highway System

The economic losses due to travel-time increases and trip reductions are computed as the product of a unit loss and the area of the trapezoid in Figure 6-1 that is defined by P_1 and P_2' and D_1 and D_2. Within this trapezoid, the losses due to travel-time increases are represented by the area of the rectangle that is defined by P_1, P_2', and D_2. The corresponding losses due to trips foregone are represented by the area of the triangle defined by P_1 and P_2' and D_1 and D_2 multiplied by the unit loss. These concepts are discussed more fully in the description of the REDARS™ 2 variable-demand network-analysis procedure that is provided in Chapter 5 and Appendix I.

6.5 UNIT LOSSES

In the above approach, the unit loss represents the cost (in dollars per hour per passenger-car-unit) of the travel-time delays and trips foregone. These unit losses will depend on the type of trip (i.e., automobile vs. freight type 1, freight type 2, etc.) and will also vary for different regions of the United States. Werner et al. (2000) used a unit-cost estimation procedure that Caltrans applied to estimate economic losses due to disruption of the Los-Angeles area highway system by the 1994 Northridge Earthquake. This procedure applies user-specified estimates of such factors as vehicle occupancy rates, truck-trip dollar value, cost of excess fuel, etc. to develop these unit costs.

The default unit costs that are currently used in REDARS™ 2 are based on data for the greater Los Angeles area that were based on traffic-congestion statistics developed by the Rand Corporation of California (and obtained from their website, which is http://ca.rand.org). Based on these studies, REDARS™ 2 uses default unit losses of $13.45/(pcu-hour) for automobile trips and $71.05/(pcu-hour) for commercial-vehicle (freight-transport) trips. These unit losses were used in the demonstration application of REDARS™ 2 to the Los Angeles area highway system that is described in Chapter 7.

As noted above, these unit costs will vary for different regions of the United States. Therefore, REDARS™ 2 users from regions outside of the greater Los Angeles area should not use the unit-cost values that are given above. Instead, it is important that these users obtain unit-cost values from data sources that are most appropriate for their particular region.

CHAPTER 7: DEMONSTRATION APPLICATION

7.1 OBJECTIVE AND SCOPE

This chapter describes a demonstration application of the REDARS™ 2 SRA methodology and software to a highway system that extends through a significant section of the greater Los Angeles (LA), California area, and is hereafter referred to as the LA-testbed highway system (see Section 7.2). This analysis will show how REDARS™ 2 can be applied to a major highway system and, in addition, will illustrate how REDARS™ 2 can be used to guide seismic-risk-reduction decision-making by estimating how each candidate risk-reduction-option affects losses due to traffic-flow and travel-time disruptions.

The demonstration SRA consists of three applications of REDARS™ 2 to this highway system, all of which are based on earthquake events contained in a new Coastal California walkthrough table that specifies earthquake occurrences over a 10,000-year time period (App. B). The first application, which is described in Section 7.3, consists of a deterministic analysis of the highway system (without uncertainties) subjected to a single earthquake in the walkthrough table. It illustrates the variety of results that REDARS™ 2 can provide for a system subjected to a single earthquake, in terms of: (a) the distribution and intensity of the earthquake-induced ground-motion and permanent ground displacement (PGD) hazards throughout the highway network; (b) the extent of the damage to the various highway components (bridges, approach fills, pavements, and tunnels) caused by these hazards; (c) how this damage affects post-earthquake travel times and trip demands; and (d) losses due to any travel-time disruptions and trip-demand increases that may occur. As noted earlier, these losses can be represented as economic losses, reduced access to key locations in the region, and/or reduced travel times along key routes that may be important to the emergency response and recovery of the region.

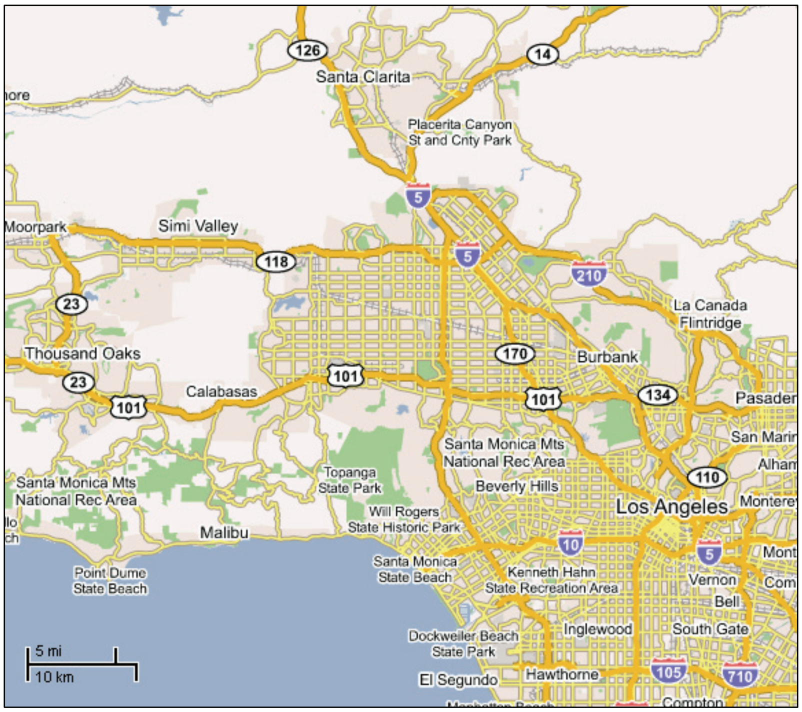
The remaining two applications of REDARS™ 2 within this demonstration application are probabilistic. The first of these applications (described in Section 7.4), is based on the same highway-system and component attributes as considered in the deterministic analysis, and provides the same types of results. However, now, the analysis accounts for how these results are affected by uncertainties in earthquake occurrence and in the estimation of seismic hazards and component damage states. This involves the development of multiple simulations for multiple earthquake scenarios listed in the Coastal California walkthrough table (Chapter 2).

The last application (Section 7.5) involves use of REDARS™ 2 results to assess the economic viability of bridge retrofits within the LA-testbed system. It is based on results from two REDARS™ 2 probabilistic analyses of this system, in which one includes the small number of bridge column-jacketing retrofits that were in place at the time of the 1994 Northridge Earthquake, and the second includes the additional bridge retrofits that were constructed through 2004. The efficacy of these additional retrofits is assessed by computing their benefit-cost ratio (where the benefits include reduction of future losses due to estimated repair costs, travel-time delays, and trips foregone), and also by comparing the variances of the loss results for these two cases (which are a measure of how the uncertainties in the estimates of these losses are reduced by the additional retrofits).

7.2 MODELS

7.2.1 HIGHWAY SYSTEM

Figure 7-1 shows the LA-testbed highway system that is considered in this analysis. This system extends from the town of Santa Clarita to the north to beyond the Century Freeway (I-105) to the south, and from the Pacific coast east to just beyond downtown LA.



Source: http://maps.google.com

Figure 7-1. LA-Testbed Highway System

The REDARS™ 2 model of this system (Fig. 7-2) includes all of the system's freeways and major arterials. It contains 1,694 nodes and 5,100 links, whose locations and traffic capacities are obtained from the Highway Performance Monitoring System (HPMS) and the National Highway Planning Network (NHPN), as accessed by the REDARS™ 2 Import Wizard (App. C).

7.2.2 BRIDGES

This highway system contains 944 bridges, of which 288 have been retrofitted by column jacketing (see Fig. 7-3), as well as 1,709 pavement links and 5 tunnels. The attributes of the various bridges are based on data from the National Bridge Inventory (NBI) database, as accessed by the REDARS™ 2 Import Wizard. Those bridges that have been column jacketed as of the end of 2004 have been identified from the California Department of Transportation (Caltrans) statewide bridge database (Yashinsky 2005). The structural capacities of these column-jacketed bridges were estimated by multiplying the un-retrofitted-bridge capacities by damage-state-dependent enhancement factors that were developed by Shinozuka (2004).

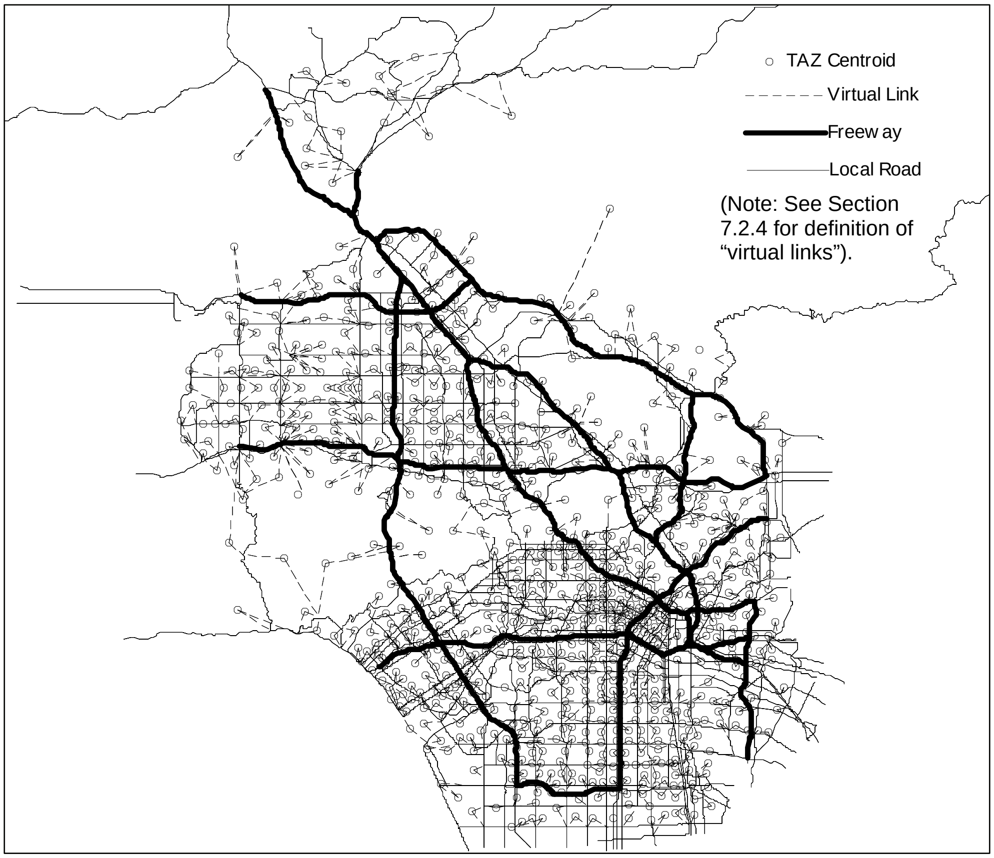


Figure 7-2. REDARS™ 2 Model of LA-Testbed Highway System

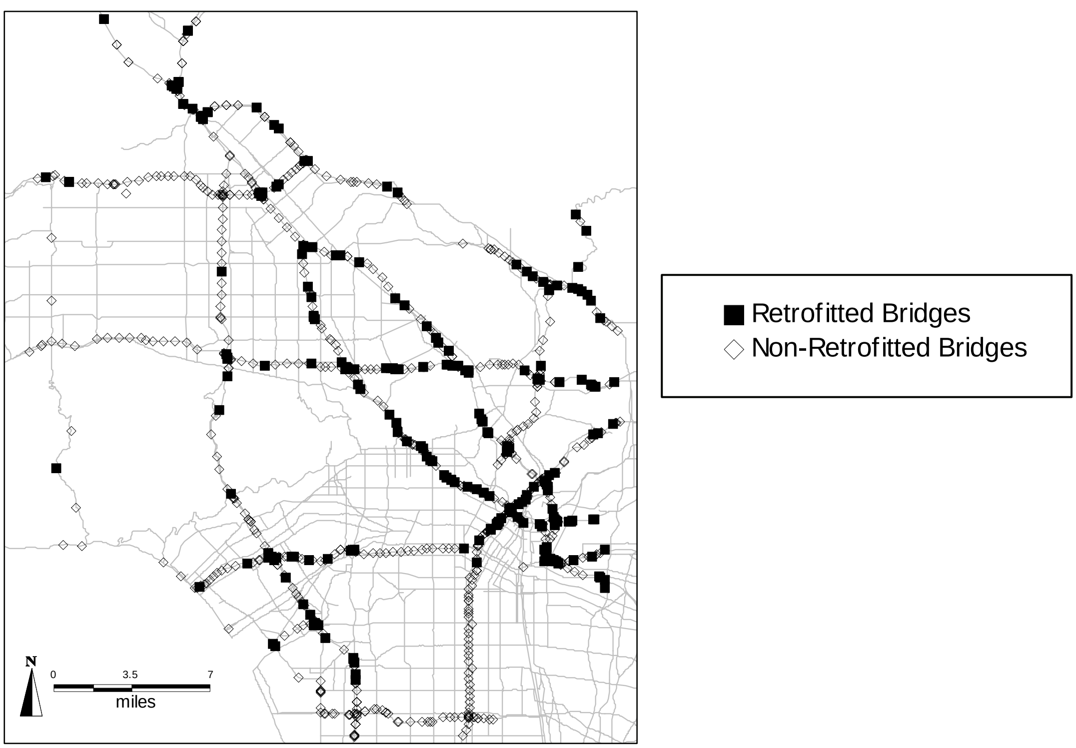


Figure 7-3. Locations of Bridges in LA-Testbed Highway System

7.2.3 SOIL CONDITIONS

The soils along the roadways in this system consist of soft rock and firm soils, which are represented in REDARS™ 2 primarily as NEHRP site classifications C and D (see Fig. 7-4). None of the soils within the system are considered to be prone to liquefaction hazards.

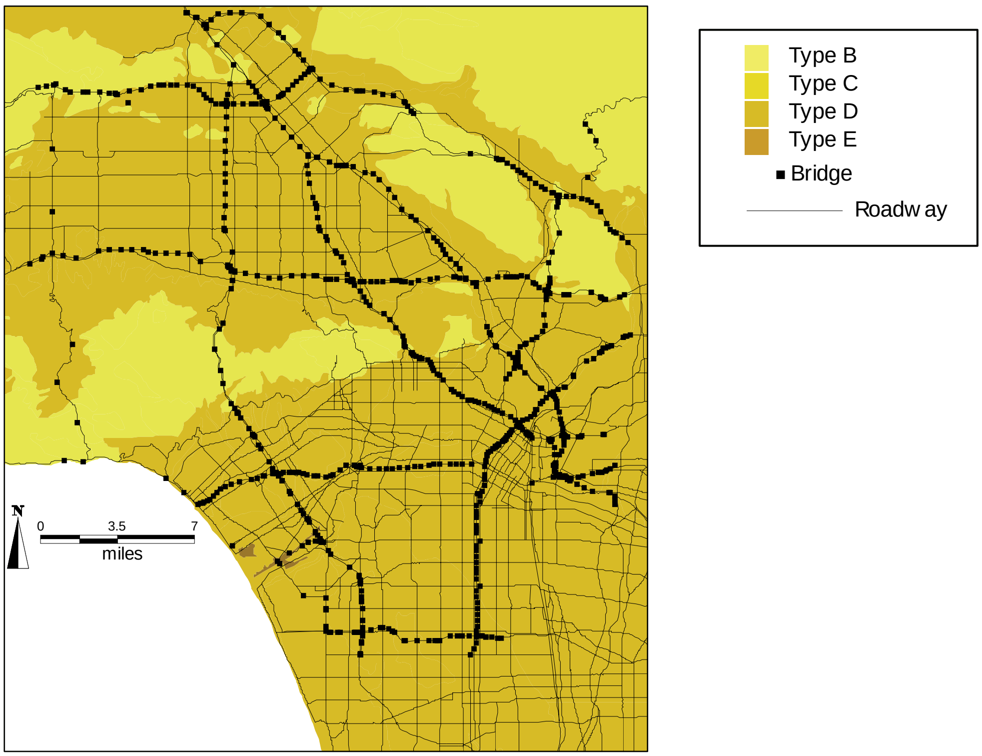


Figure 7-4. Soil Conditions (in terms of NEHRP Site Classifications) Throughout LA-Testbed Highway System

7.2.4 TRAFFIC ANALYSIS ZONES

Figure 7-5 shows the section of the greater LA area within which this highway system is located. This area is modeled using 977 traffic analysis zones (TAZs) whose locations and trips to all other zones are based on data obtained from the Southern California Area of Governments (SCAG). In addition, 59 external TAZs are included that represent aggregations of trips into and out of the region from locations beyond the region are included in this model. In this REDARS™ 2 model, 3,908 virtual links are used to connect the centroid of each TAZ to the actual highway system (see Fig. 7-2).

Several of these TAZs are highlighted in Figure 7-5. These TAZs represent those particular zones for which earthquake-effects on trips and travel times to-and-from the zones at different times after each earthquake scenario are displayed as output from this analysis. They were selected because they represent centers of commerce, locations of major medical centers, and locations of airports and other facilities that could be important for post-earthquake emergency response and recovery.

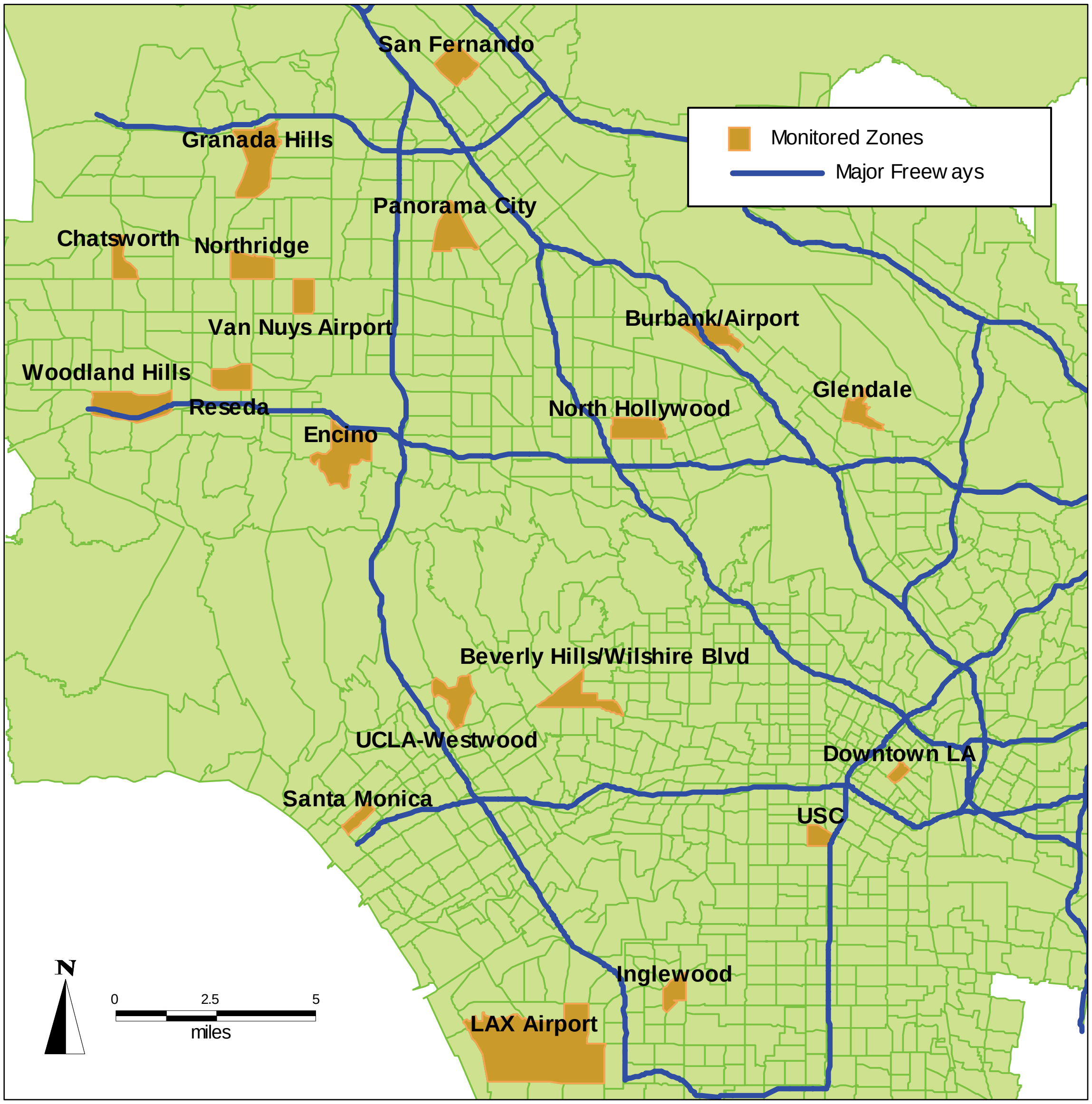
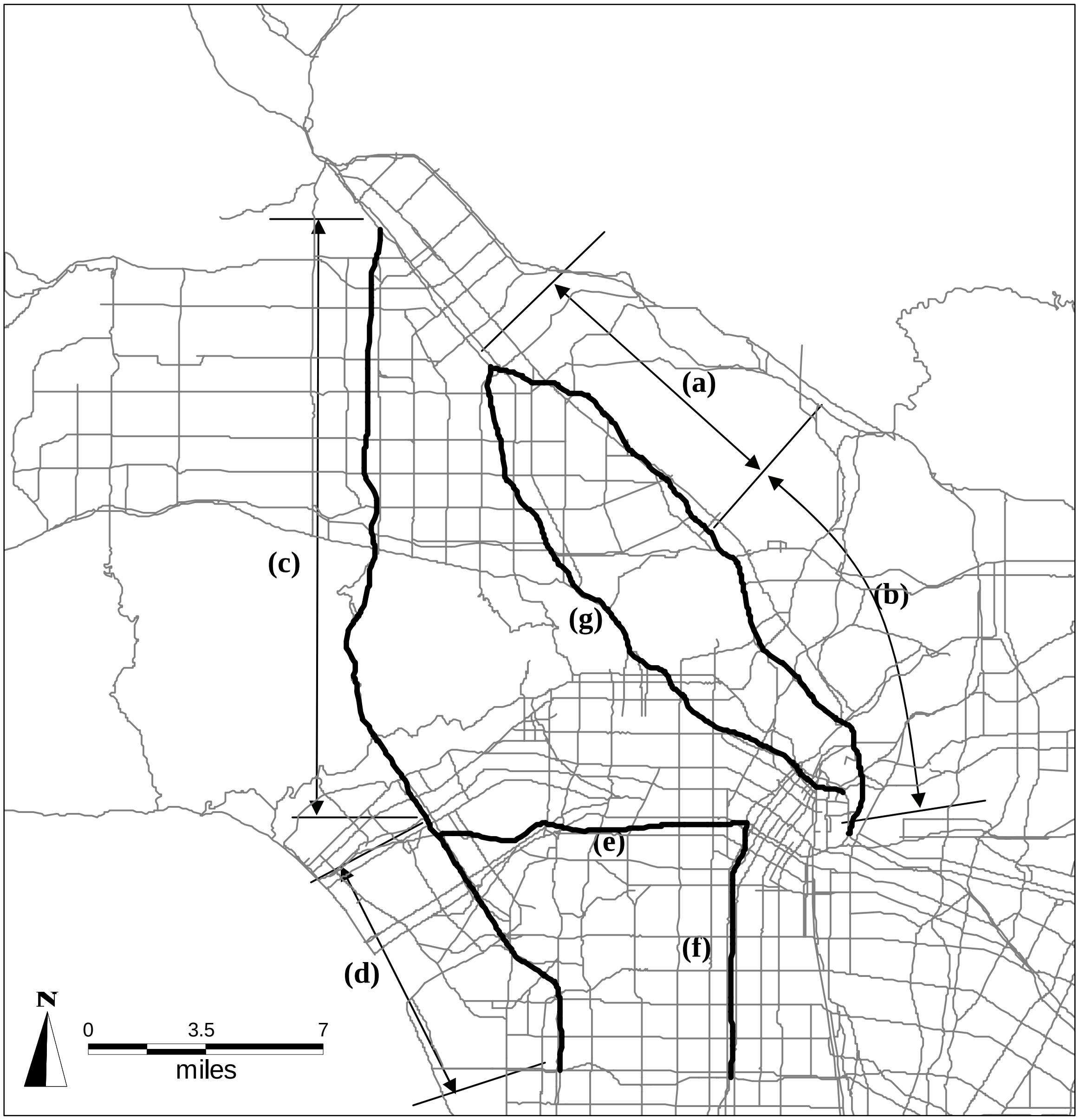


Figure 7-5. Traffic Analysis Zones whose Travel-Times and Trips to/from These Zones are Displayed as Output from this Demonstration Application

7.2.5 ROUTES

Figure 7-6 shows selected routes within this LA-testbed highway system whose post-earthquake travel times have been displayed as output from this demonstration application. Of course, any number of additional or alternative routes within this system could also have been selected for travel-time display.

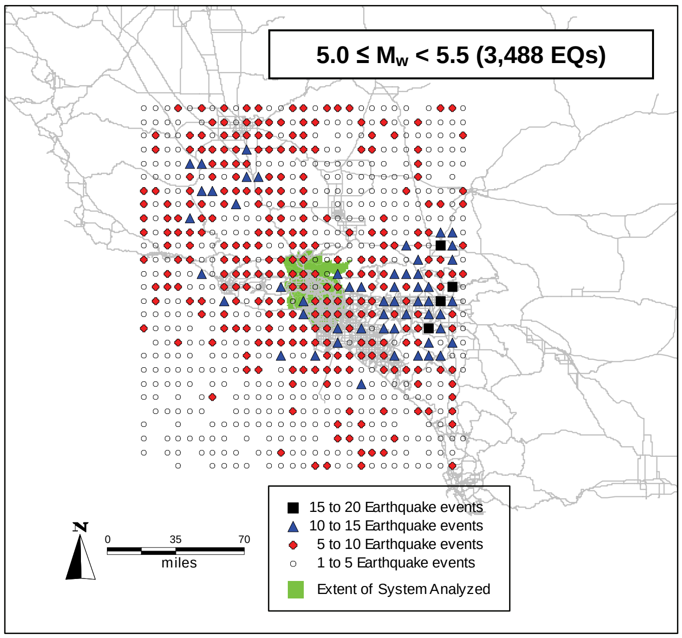


(a) I-5 from San Fernando to Burbank
(b) I-5 from Burbank to downtown LA
(c) I-405 from I-5 to I-10 interchange
(d) I-405 from I-405/I-10 interchange to LAX
(e) I-10 from Santa Monica to downtown LA
(f) I-110 from I-105 to downtown LA
(g) I-101 from I-405 interchange to downtown LA

Figure 7-6. Routes whose Travel Times are Displayed as Output from This Demonstration Analysis

7.2.6 EARTHQUAKE SCENARIOS

The earthquake scenarios for this analysis are those events from the overall 10,000-year Coastal-California walkthrough table (App. B) that are located within about two-hundred miles of this LA-testbed highway system. They consist of 7,035 earthquakes with $M_w \geq 5.0$, whose breakdown by moment magnitude is shown in Figure 7-7. Of these, it turns out that 2,645 of these events actually caused damage to this system (see Sec. 2.4.1.4 of Chap. 2). Only these damaging events were considered in the probabilistic SRAs described in Sections 7.4 and 7.5.



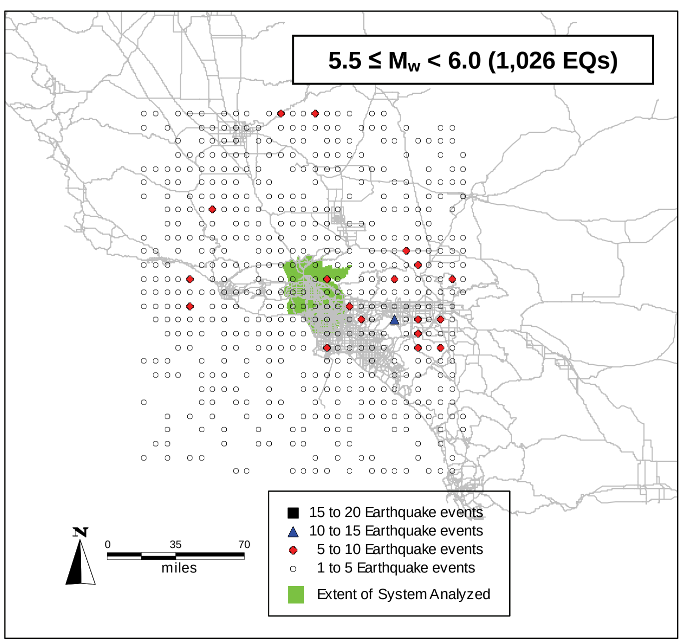
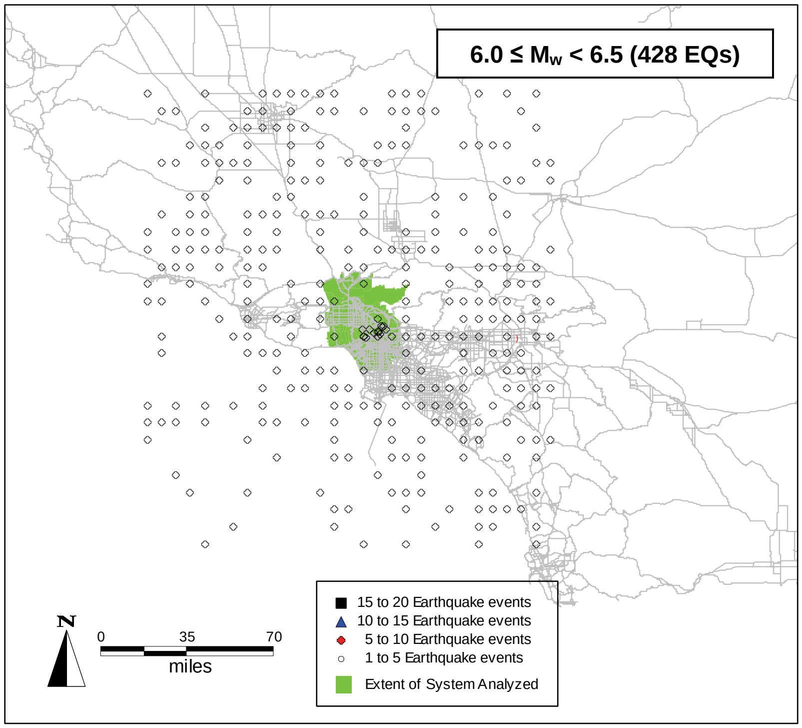


Figure 7-7. Epicenters of Earthquake Scenarios in 10,000-Year Walkthrough Table



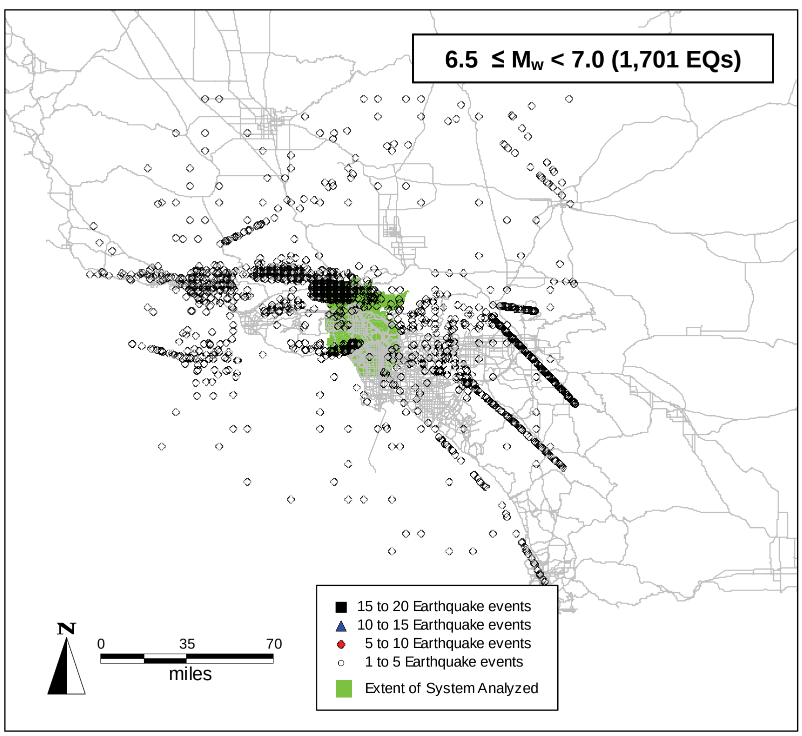
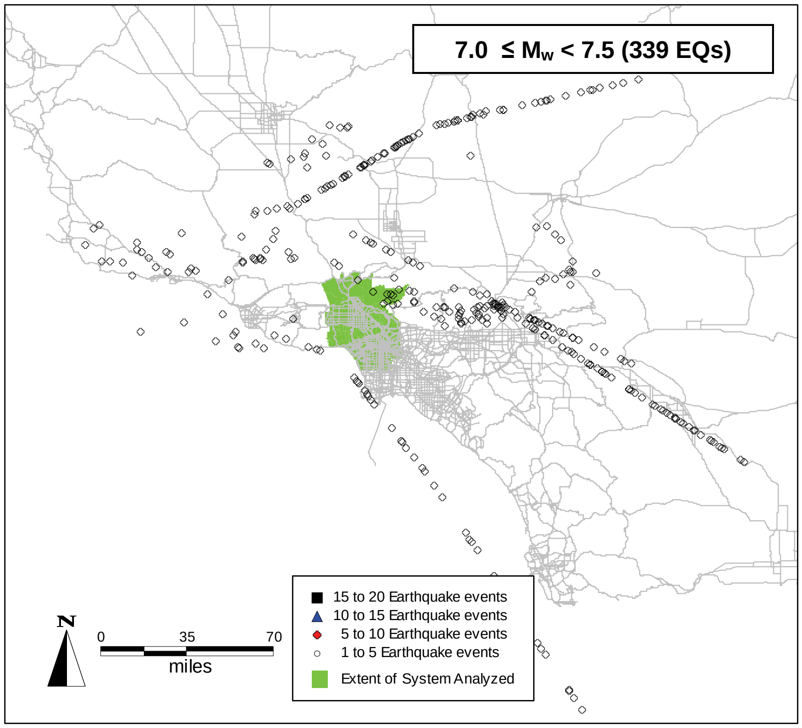


Figure 7-7. Epicenters of Earthquake Scenarios in 10,000-Year Walkthrough Table (continued)



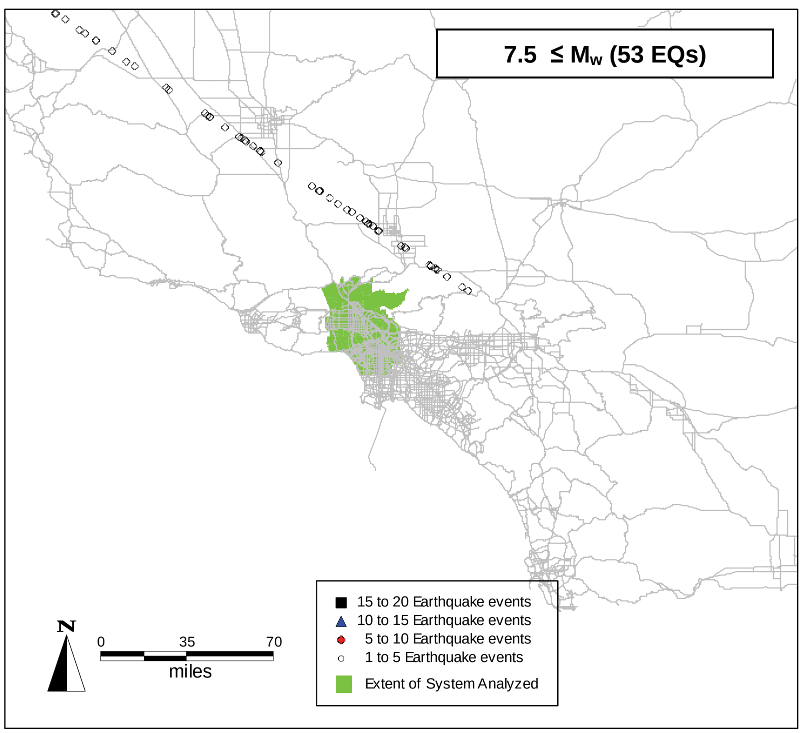


Figure 7-7. Epicenters of Earthquake Scenarios in 10,000-Year Walkthrough Table (concluded)

7.3 DETERMINISTIC ANALYSIS

The first part of this demonstration application consists of a deterministic analysis of the seismic performance of the LA-testbed highway system subjected to a single earthquake scenario. This analysis does not include effects of uncertainties; i.e., mean values of all uncertain parameters are used throughout the analysis. Its purpose is to illustrate the types of results that REDARS™ 2 can provide for such analyses, and how they can be interpreted.

7.3.1 EARTHQUAKE SCENARIO

The earthquake scenario used in this deterministic analysis has a moment magnitude of 6.6 and is caused by rupture along the Santa Monica Fault. This scenario occurs during Year 3,076 in the walkthrough table used in the probabilistic analyses of this LA-testbed system (see Secs. 7.4 and 7.5). The epicenter of this earthquake is located within the Pacific-Palisades/Santa-Monica area, about 2.5 km inland from the Pacific-Ocean coastline (e.g., Fig. 7-8).

The Santa Monica Fault is a reverse fault with a dip angle of 75 deg. The surface expression of the fault rupture for the above earthquake scenario is about 28-km. long and about 9.7 km wide[5]. It extends in a northeast direction from its origin in the Pacific Ocean along a path that parallels Sunset Boulevard to its terminus that is about five km beyond the San Diego Freeway (e.g., Fig. 7-8a). The hypocentral depth of this earthquake is about 8.2 km. Because of this depth and the dip angle of this reverse fault, the following figures show that earthquake's epicenter is slightly offset from its surface expression of fault rupture.

7.3.2 SEISMIC HAZARDS

7.3.2.1 Ground Shaking

Figure 7-8 shows the distribution and intensity of ground motions throughout this highway system that are caused by this earthquake scenario. These ground-motion results are provided as spectral accelerations at a period of 1.0 sec., since this is the ground-motion parameter that is used by the REDARS™ 2 default models for estimating bridge damage due to ground shaking (see App. G). However, REDARS™ 2 can also provide ground-motion results in terms of spectral acceleration at a period of 0.3 sec. (which is used by this bridge damage model for a few situations) and also as peak ground acceleration (which is often used in the calculation of liquefaction hazards).

These figures show that the intensity of the ground motions due to this earthquake scenario is largest at bridge sites along I-405 that are close to the fault rupture. At these sites, the spectral accelerations are as high as 0.83 g. However, significant ground shaking (on the order of 0.6 g to 0.8 g) also occurs along some segments of I-10 that are west of I-405.

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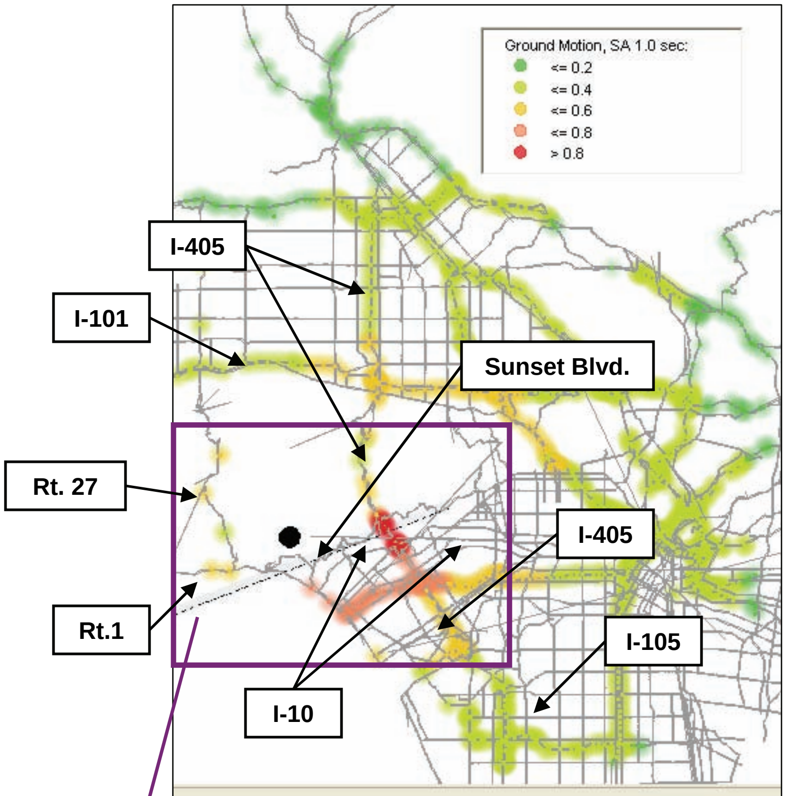
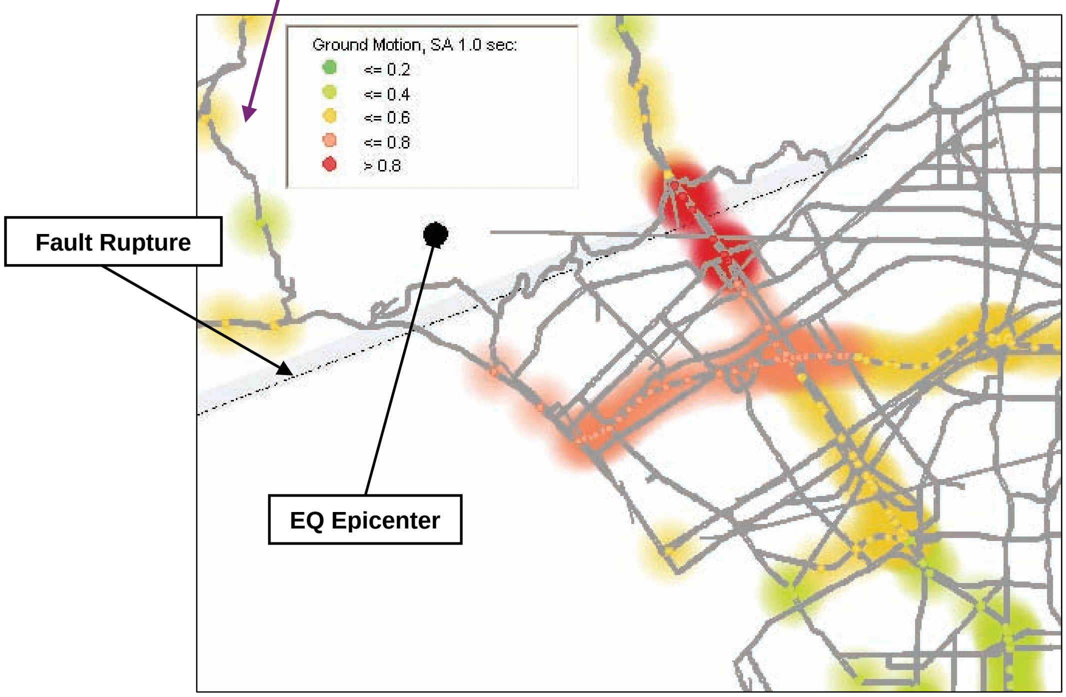
[5] As described in Appendix B, the lengths and widths of the fault rupture for each earthquake scenario are estimated from Wells and Coppersmith (1994), including uncertainties. Uniform random variates are used to estimate the location of the epicenter within the projection of the fault plane onto the ground surface.



a) System-Wide Ground Motions



b) Area with Most Severe Ground Motion

Figure 7-8. Ground Motions (Spectral Acceleration at Period of 1.0 sec., in units of g)

7.3.2.2 Surface Fault Rupture

In addition to ground shaking, this earthquake scenario causes significant surface-fault-rupture hazards, with estimated permanent ground displacements of up to 26 in. Figure 7-9 shows that these hazards occur over an extended length of Sunset Boulevard, which seems plausible in view of the close proximity of this major roadway to the Santa Monica Fault.

This figure also shows significant fault-rupture displacements along a length of the Pacific Coast Highway (Route 1) that extends from Sunset Boulevard to Route 27. However, only the small segment of Route 1 that is actually within the zone of deformation of the Santa Monica fault rupture could undergo large displacements. This result is attributed to the modeling of this entire roadway segment by a single link (only a small part of which is actually in the fault-rupture zone) and also by the REDARS™ assumption that the ground displacement of any link in the network is governed by the largest displacement occurring anywhere along that link.

Figure 7-9 also shows large ground displacements along a long segment of Route 27 north of Route 1 (also modeled by a single link) and at the sites of two bridges along Route 1 just west of Route 27. Later sections of this chapter show that these displacements cause failure of these two bridges and along Route 27, leading to extended roadway closures in this localized area of the LA-testbed system. However, these results are somewhat counterintuitive, since the locations of the failures are not immediately adjacent to the ruptured fault segment. Thus, possible causes of these results will be further assessed by the REDARS™ development team. It is interesting to note that estimated fault-rupture displacements outside of this localized area and throughout the remainder of the LA-testbed highway system are much more consistent with intuition.

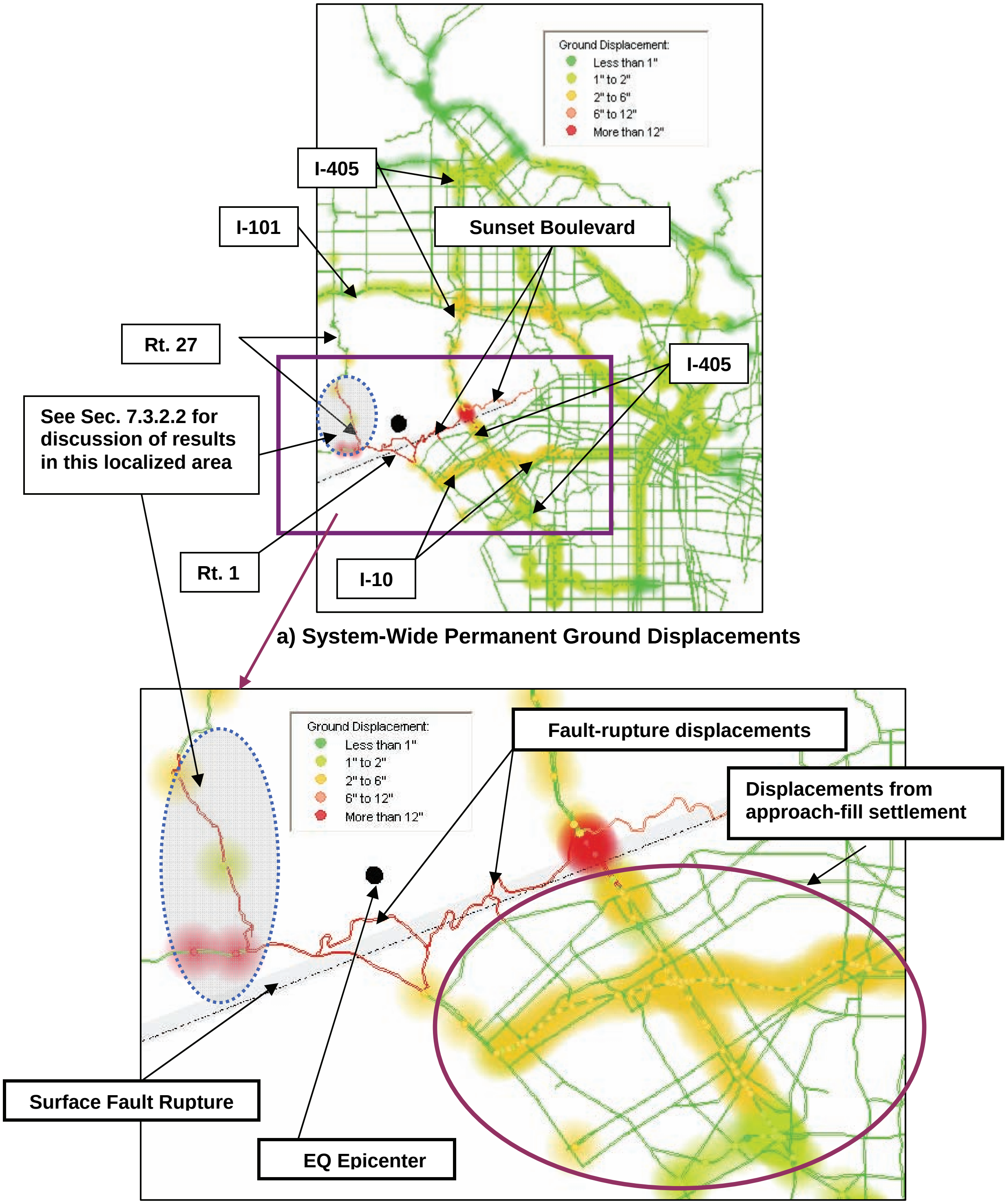
7.3.2.3 Approach Fill Settlement

Figure 7-9 also displays permanent ground displacements from approach-fill settlement. These small-to-moderate displacements are generally on the order of just a few inches.

7.3.3 COMPONENT PERFORMANCE

The seismic performance of the various components is this highway system is summarized in Table 7-1. This table shows that 20 of the 944 bridges in the system are estimated to suffer complete damage (i.e., collapse) and 31 additional bridges are estimated to experience extensive damage. The table also indicates complete damage to 54 of the system's 9,008 pavement links, and extensive damage to 10 of these links. The various tunnels in the system were not damaged, and the approach fills experienced only slight damage.

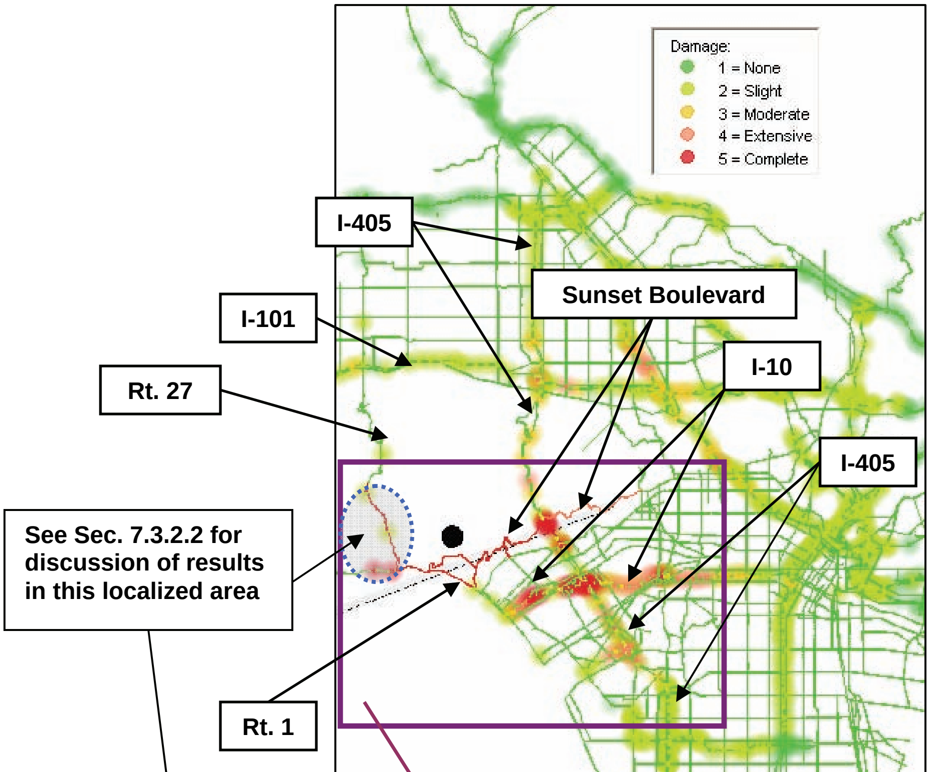
Figure 7-10 provides a map of the LA-testbed highway system that shows the locations of the various damaged components within this system. This figure shows that most of the collapsed bridges are located along the segment of I-405 between Sunset Boulevard and I-10, and also along I-10 between its western terminus and its interchange with I-405. The roadway-pavement segments that experience extensive or complete damage correspond to those segments that experience large ground displacements due to surface fault rupture, and are located within the estimated width of the fault-rupture zone.



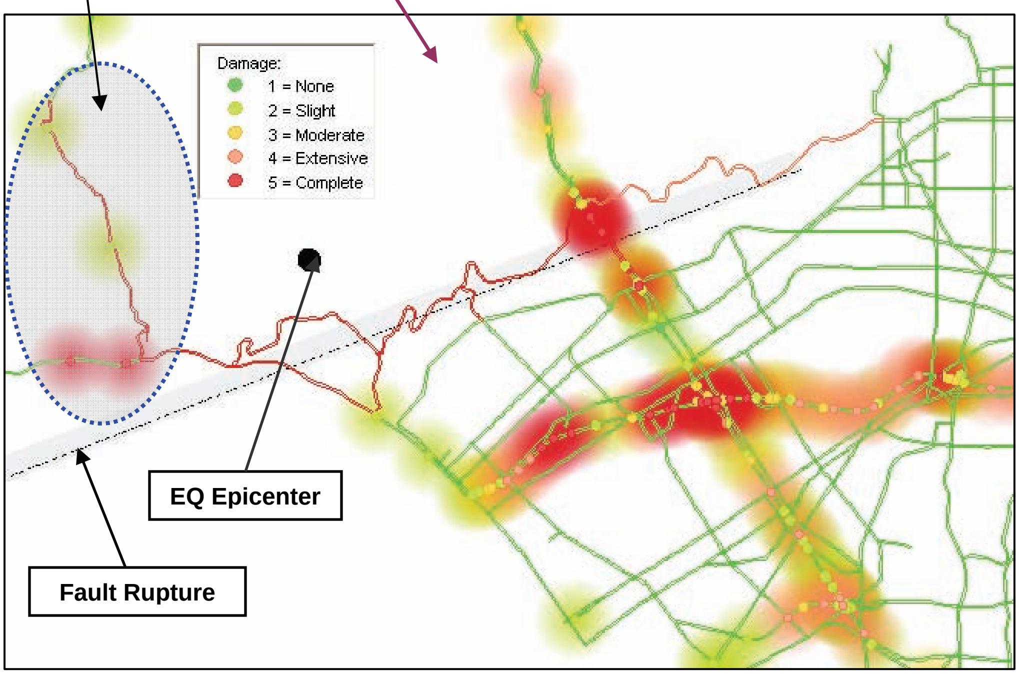
a) System-Wide Permanent Ground Displacements

b) Area with Largest Permanent Ground Displacements (from Surface Fault Rupture)

Figure 7-9. Permanent Ground Displacement from Surface Fault Rupture and Approach-Fill Settlement



a) System-Wide Damage



b) Area with Greatest Damage to Components

Figure 7-10. Component Damage States

Table 7-1. Component Damage Summary

Damage State	Bridges	Approach Fills	Tunnels	Pavement Links
1. None	744	400	5	8,944
2. Slight	93	1,309	0	0
3. Moderate	56	0	0	0
4. Extensive	31	0	0	10
5. Complete	20	0	0	54
Totals	944	1,709	5	9,008

Examination of the data contained in Table 7-2 clarifies why this large number of bridge collapses has occurred. This table lists seismic-design, seismic-retrofit, and structural-attribute data for the 20 collapsed bridges and five nearby bridges that did not collapse, as well as each bridge's seismic hazards and damage state. The following trends are noted from this list:

- Five of the bridges (those highlighted with light blue shaking in Table 7-2) are estimated to have collapsed due to excessive fault-rupture displacement. Three of these collapsed bridges are located on I-405 near Sunset Boulevard, near the crossing of I-405 by the fault rupture crosses I-405. The two remaining collapsed bridges are located along Route 1 just west of Route 27, and are attributed to the fault-displacement issues discussed in Section 7.3.2.2.

- The remaining 15 bridges (highlighted with light grey shading in Table 7-2) are estimated to have collapsed due to strong ground shaking. Table 7-2 shows that all of these bridges are multi-span structures that were neither seismically designed (i.e., constructed prior to 1975) nor column jacketed. That is, no seismically-designed or column-jacketed bridge is estimated to have collapsed due to ground shaking from this earthquake scenario.

- Table 7-2 lists five un-collapsed bridges that are adjacent to the above 15 collapsed bridges. Two of these bridges (which are numbered 231 and 264 in Table 7-2 and are highlighted with turquoise shading) are neither seismically designed nor retrofitted, but are single-span structures. The REDARS™ 2 default bridge model indicates that such bridges have very robust seismic-performance characteristics.

- The three remaining non-collapsed bridges are numbered 211, 224, and 244 and are shown by orange shading. These are multi-span bridges that have either been seismically designed or retrofitted with column jacketing. They are near multi-span collapsed bridges that were neither seismically designed nor retrofitted (see Table 7-2 footnote).

Of course, the above trends should be interpreted with due regard to the various approximations that are inherent in the current REDARS™ 2 default bridge model, and in the use of mean values of all uncertain input parameters in this analysis (Chap. 4). Nevertheless, they do provide some indication of the possible effectiveness of modern seismic design and retrofit procedures in reducing the level of bridge damage due to strong ground shaking.

Table 7-2. Collapsed Bridges and Nearby Uncollapsed Bridges from Scenario Earthquake along Santa Monica Fault

ID No.	Bridge Number	Approximate Location	EQ Design (Year. Built)	Column Jacket Retrofit	Ground Motion (Spectral Acceleration at T = 1 sec) (GM)	Fault-Rupture Displacement (FRD)	Damage State	
							GM	FRD
285	53 036S	On Hwy 1, 1.68 km west of Rt. 27	No (1940)	No	0.54 g	22.9 in.	1	**5**
283	53 003S	On Hwy 1, just west of Rt. 27 (single-span)	No (1933)	No	0.54 g	24.2 in.	1	**5**
392	53 10425	On I-405 0.35 km south of Sunset Blvd OC	No (1956)	No	0.83 g	16.8 in.	2	**5**
390	53 10415	On I-405 0.40 km south of Sunset Blvd OC	No (1956)	No	0.83 g	16.8 in.	3	**5**
388	53 2390	On I-405 0.45 km south of Sunset Blvd OC	Yes (1975)	No	0.83 g	16.8 in.	4	**5**
339	53 0710	At interchange between I-405 and I-10???	**No (1957)**	**No**	0.81 g	0.0 in.	**5**	1
161	53 1597	On I-10 1.95 km NE of Highway 1	**No (1965)**	**No**	0.65 g	0.0 in.	**5**	1
163	53 1598	On I-10 2.40 km NE of Highway 1	**No (1965)**	**No**	0.66 g	0.0 in.	**5**	1
168	53 1599	On I-10 2.8 km NE of Highway 1	**No (1963)**	**No**	0.66 g	None	**5**	1
182	53 1604	On I-10 1.6 km SW of I-405	**No (1963)**	**No**	0.64 g	None	**5**	1
205	53 1605	On I-10 1.0 km SW of I-405	**No (1963)**	**No**	0.64 g	None	**5**	1
207	53 1620	On I-10 1.0 km SW of I-405	**No (1963)**	**No**	0.64 g	None	**5**	1
219	53 0939	On I-10 just SW of I-405	**No (1963)**	**No**	0.63 g	None	**5**	1
220	53 1628	On I-10 just SW of I-405	**No (1963)**	**No**	0.63 g	None	**5**	1
209	53 1638G	On I-405 just south of I-10	**No (1963)**	**No**	0.62 g	None	**5**	1
211*	53 1630G	On I-405 just south of I-10	No (1963)	**Yes**	0.62 g	None	**3**	1
223	53 1623	On I-405 just south of I-10	**No (1963)**	**No**	0.63 g	None	**5**	1
220	53 1628	On I-405 just south of I-10	**No (1963)**	**No**	0.63 g	None	**5**	1
226	53 1640	On I-10 just east of I-405	**No 1964)**	**No**	0.62 g	None	**5**	1
224*	53 1637F	On I-10 just east of I-405	No (1964)	**Yes**	0.63 g	None	**3**	1
229	53 1634	On I-10 about 0.9 km east of I-405	No (1964)	No	0.62 g	None	5	1
231	53 1617	On I-10 about 1 km east of I-405 **(single span)**	No (1963)	No	0.61 g	None	**1**	1
245	53 2791S	On I-10 about 5.3 km east of I-405	**No (1964)**	**No**	0.50 g	None	**5**	1
244*	53 2791	On I-10 about 5.3 km east of I-405	**Yes (1994)**	No	0.50 g	None	**2**	1
264	53 1611S	On I-10 about 5.3 km east of I-405 **(single span)**	No (1964)	No	0.50 g	None	**1**	1

* Note: Retrofitted and un-collapsed Bridge 211 is near collapsed Bridges 209, 223, and 220; retrofitted and un-collapsed Bridge 224 is next to collapsed Bridge 226, and un-collapsed and seismically designed Bridge 244 is near collapsed Bridge 245.

7.3.4 SYSTEM STATES

After the component damage states are estimated, the REDARS™ 2 component-repair model is used to estimate corresponding repair costs, downtimes, and the ability of the damaged component to accommodate traffic at various times after the earthquake while the repairs are proceeding. As described elsewhere in this Technical Manual, the default component-repair models that are now included in REDARS™ 2 were developed from close consultation with members of Caltrans' senior engineering and maintenance staff, in order to reflect Caltrans' experience, construction methods, and repair resources. Of course, these repair models should be modified when applying REDARS™ 2 to highway systems in other parts of the country, where experience levels, construction practices, and repair resources will usually differ from those of Caltrans.

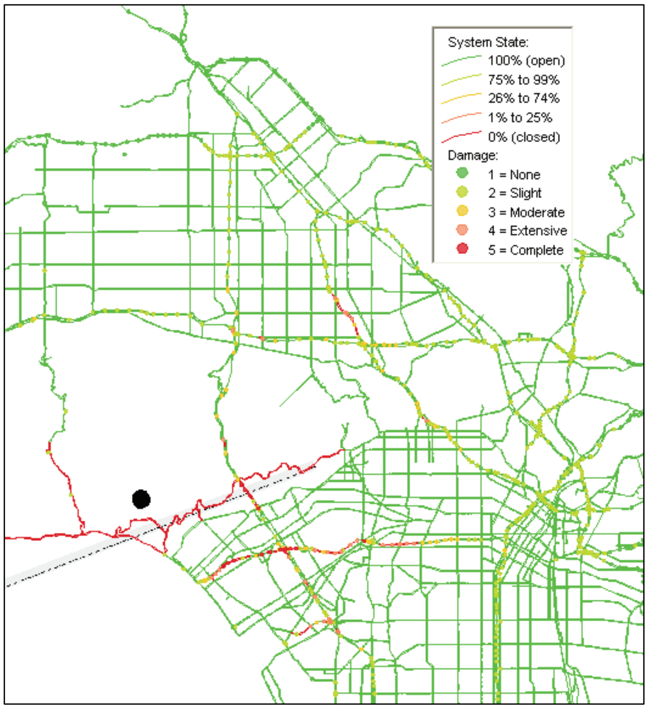
For the levels and types of component damage summarized in Section 7.3.3, these repair models result in the estimated system states shown in Figure 7-11 for four different times after the earthquake (7-, 60-, 150-, and 221-days). In this assessment, the post-earthquake time of 7-days was chosen to typify an early time after the earthquake, when repair resources are first being mobilized to begin the repairs. The post-earthquake time of 221-days is the "system recovery time" for this particular roadway system and earthquake, which is the estimated time after the earthquake when all repairs are completed and the highway system first returns to its pre-earthquake condition (according to the default component repair models described in Appendices G and H). The post-earthquake times of 60-days and 150-days represent intermediate times after the initiation of the system repairs and before the repairs are completed.

The system state at 7-days after the earthquake contains the largest number closed roadway network links along which the more severely damaged components are located. Figure 7-11 shows that the most significant closures are located: (a) along I-405 between Sunset Boulevard and I-10 and also at a few other locations; and (b) along a larger segment of I-10 that extends from its western terminus to a location that is approximately midway between its I-405 interchange and downtown Los Angeles.

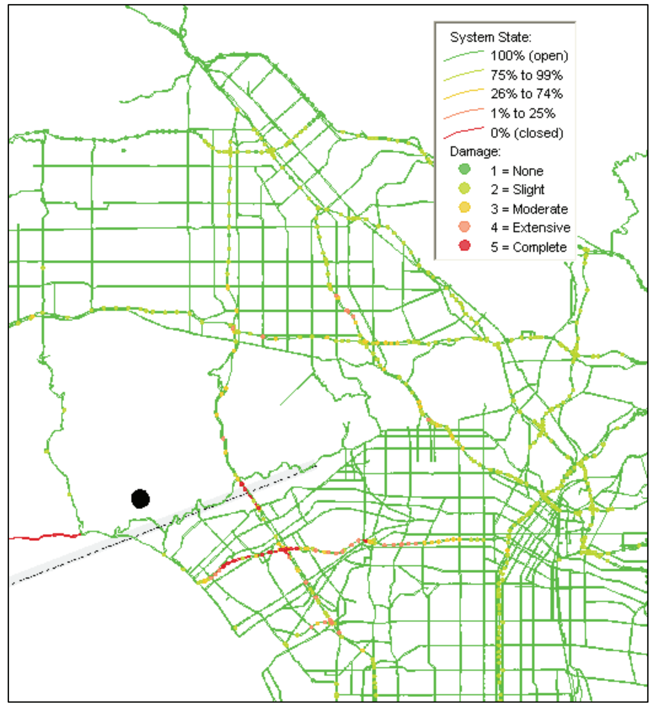
At subsequent days after the earthquake, Figure 7-11 shows that the number of closed roadway network links decreases as the repairs proceed in accordance with the REDARS™ component-repair models. These system states at successively increasing intermediate post-earthquake times will tend to converge toward the fully-open system state at the system recovery time of 221 days after the earthquake.

7.3.5 TRAFFIC AND TRIP-DEMAND IMPACTS

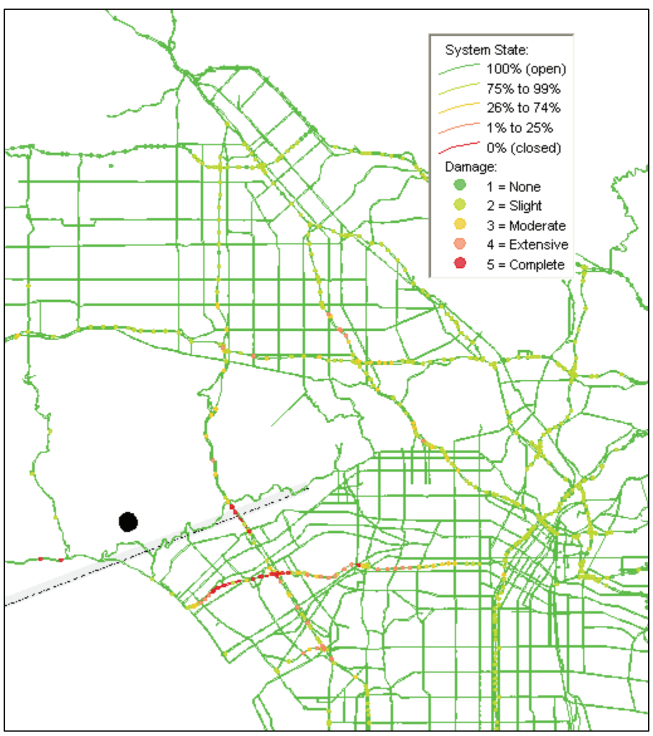
The next step in this deterministic analysis of this LA-testbed highway system consisted of application of the network analysis models described in Chapter 5 and Appendix I to each of the system states shown in Figure 7-11. These models estimate how earthquake-induced highway-system damage and associated traffic congestion affect post-earthquake travel times, traffic impacts, and trip demands on the system.



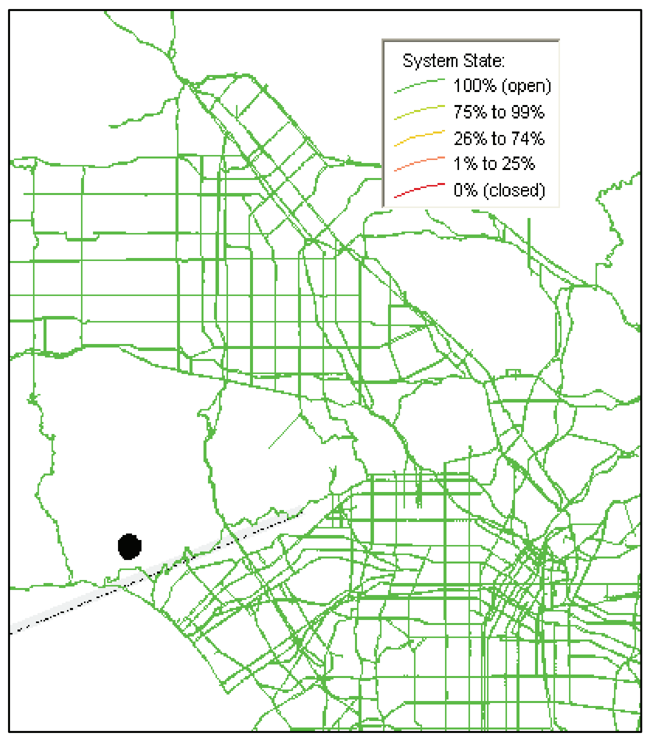
a) 7-Days after Earthquake



b) 60-Days after Earthquake



c) 150-Days after Earthquake



d) 221-Days after Earthquake

Figure 7-11. Post-Earthquake System States

Table 7-3 summarizes the estimated impacts of this earthquake scenario on available lane-miles and trip-demands at various times after the earthquake. It shows that, at 7-days after the earthquake, the total number of available lane-miles in the system is reduced by about 4-percent due to the damage experienced by the highway system, and that the trip demands on the system are reduced by about 8-percent. Table 7-3 also shows how these impacts decrease over time after the earthquake, as the repairs to the damaged components proceed.

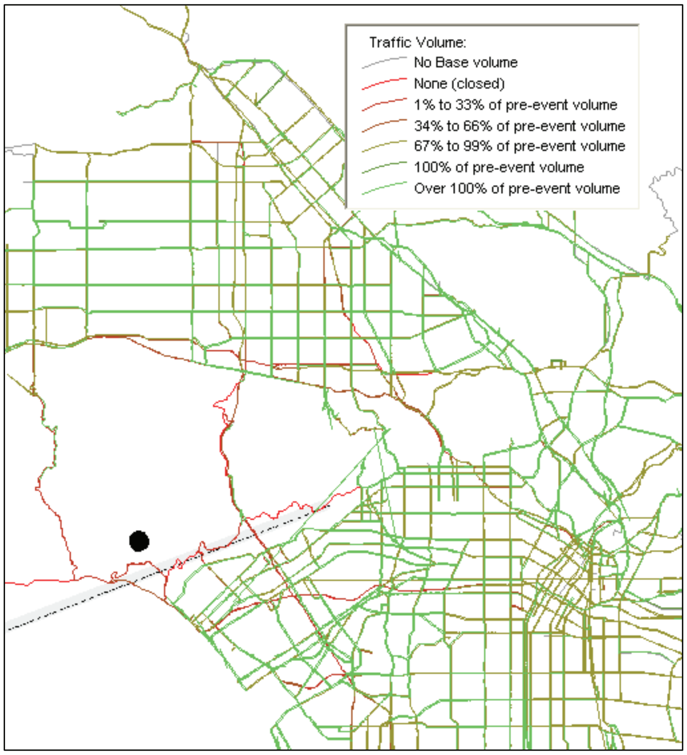
Table 7-3. Summary of Estimated Earthquake Impacts on System-Wide Traffic

Days after the Earthquake	Traffic Impactions (reductions relative to pre-earthquake)	
	Lane-Miles	Trip Demands
7 days	4%	8%
60 days	1%	3%
150 days	0%	2%
221 days (system recovery time)	0%	0%

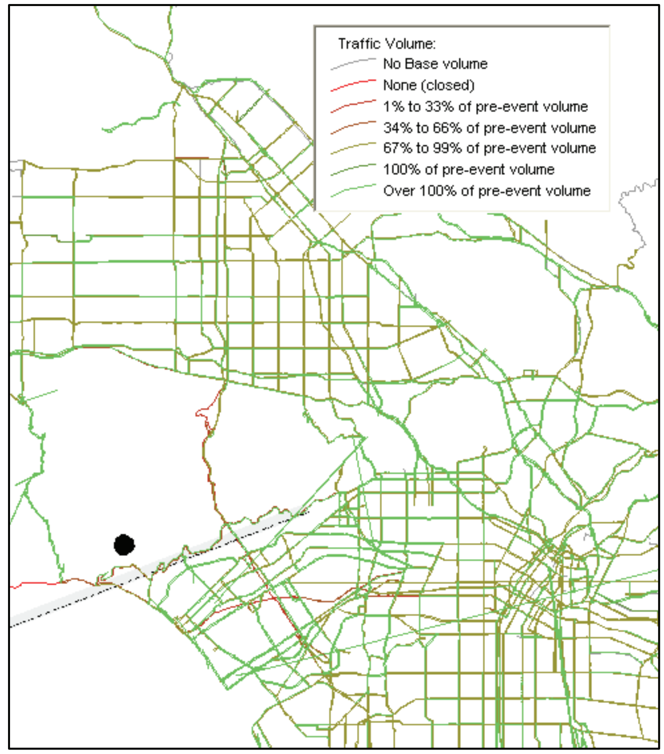
REDARS™ 2 provides several types of graphical system-wide maps and tabular data to show various traffic impacts from earthquake damage to the highway system. Graphical system-wide maps provided by REDARS™ 2 for this purpose are summarized below:

- ***System-Wide Post-Earthquake Traffic Volumes (Fig. 7-12).*** These system-wide maps show that, at 7-days after the earthquake, major sections of the I-405 and I-10 freeways in the western part of the city are estimated to be fully closed to traffic, as will sections of I-101 at the I-405 interchange, Route 1 near its crossing of the Santa Monica Fault rupture zone, and the western part of Sunset Boulevard. At 60-days after the earthquake, the freeway segments along I-405 and I-10 remain closed, but the other previously-closed highway segments can now accommodate partial pre-earthquake traffic volumes. At 150-days after the earthquake, the system-wide traffic volumes continue to improve, and only sections of I-10 remain closed. The travel volumes are restored to their full pre-earthquake levels at the system recovery time of 221-days after the earthquake.

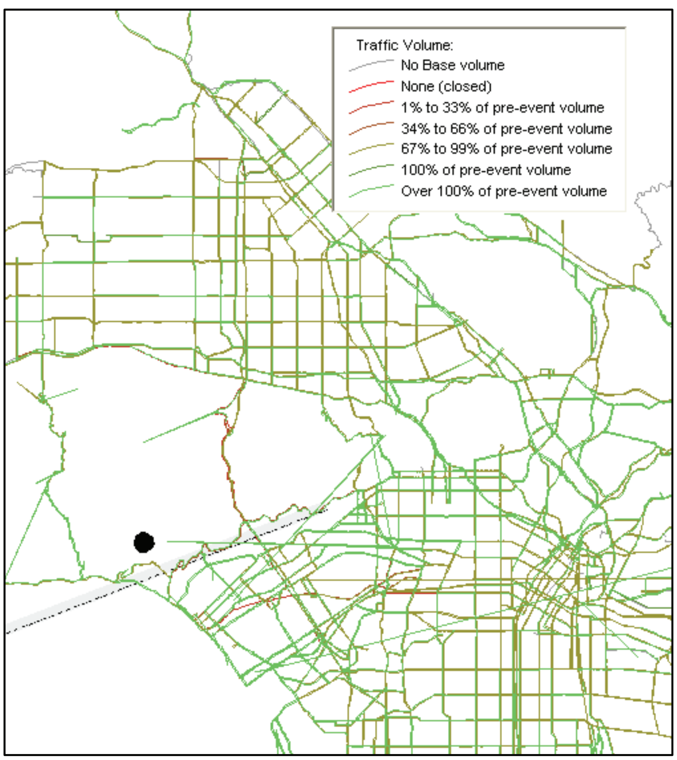
- ***System-Wide Post-Earthquake Travel Times (Fig. 7-13).*** This set of maps shows how access and egress times to/from all of the TAZs in the region are affected by earthquake damage to this highway system. Output from this analysis provides these results for both automobile and freight traffic. Figure 7-13 shows results for automobile traffic only. At 7-days after the earthquake, this figure shows that automobile travel times are affected throughout much of the western and central part of LA and also in the southern part of the San Fernando Valley. At subsequent post-earthquake times, these travel time effects diminish as the system's traffic-carrying capacity is being restored.



a) 7-Days after Earthquake



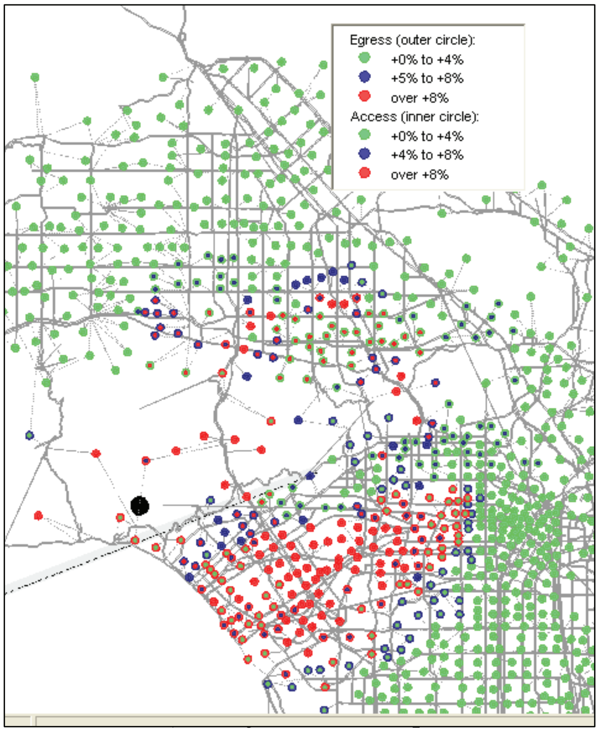
b) 60-Days after Earthquake



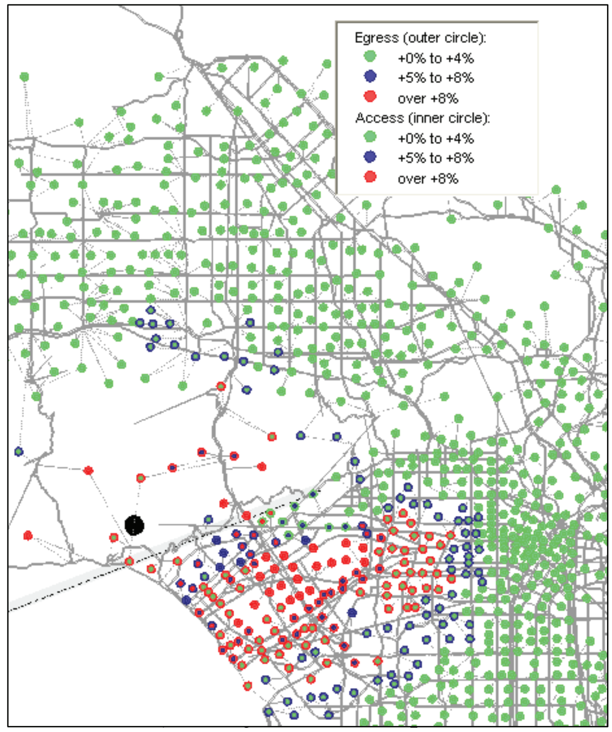
c) 150-Days after Earthquake

d) 221-Days after Earthquake

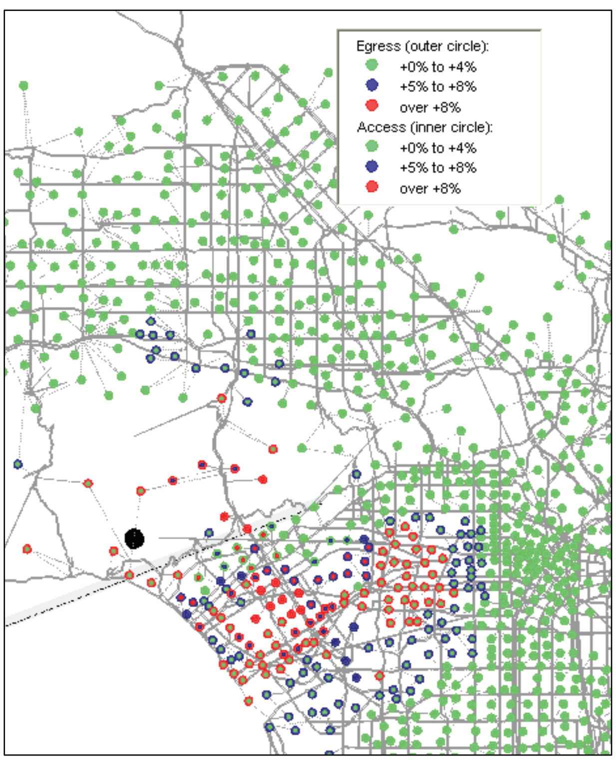
Figure 7-12. Post-Earthquake Traffic Volumes (as percentage of Pre-Earthquake Volumes)



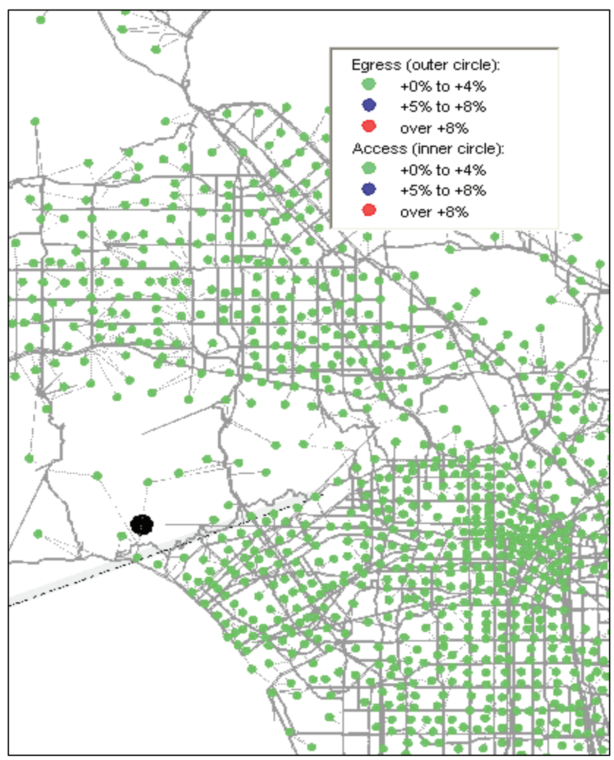
a) 7-Days after Earthquake



b) 60-Days after Earthquake



c) 150-Days after Earthquake



d) 221-Days after Earthquake

Figure 7-13. Post-Earthquake Travel-Time Increases for Automobile Trips (as percentage of Pre-Earthquake Travel Times)

- ***System-Wide Post-Earthquake Trip Demands (Fig. 7-14).*** This set of maps shows how automobile- and freight-trip demands on the LA-testbed highway system are affected by earthquake damage to the system. Figure 7-14 provides such results for automobile trips. At 7-days after the earthquake, the figure shows that the greatest reductions in automobile trip demands occur in the Santa-Monica and the western- and central-LA areas, and also in the southern part of the San Fernando Valley. At subsequent post-earthquake times, these trip demands steadily increase until, at 221-days after the earthquake, they reach their pre-earthquake levels.

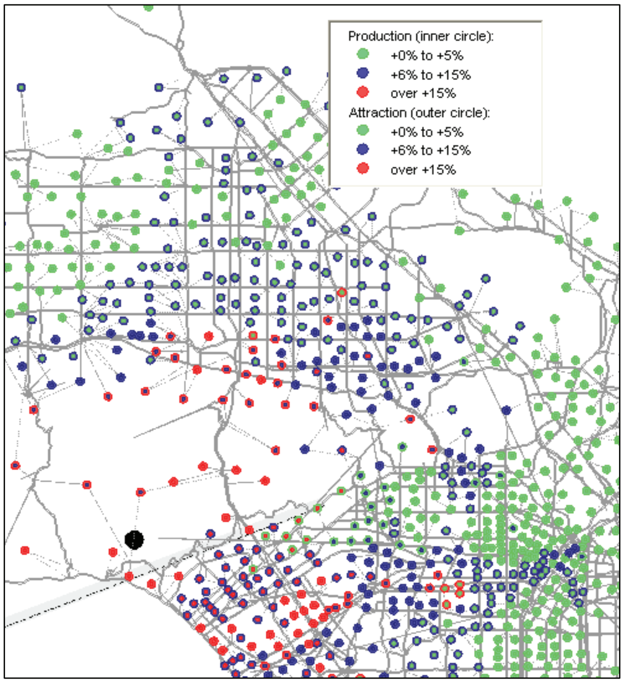
In addition to the above maps of system-wide traffic impacts, REDARS™ 2 provides additional detailed data on travel times and trip demands to/from user-designated key locations and along user-designated key routes. Tables 7-4, 7-5, and 7-6 show how the earthquake damage affects travel times and trips to/from the various locations shown in Figure 7-5, as well as travel times along the particular routes shown in Figure 7-6. Such data can be helpful for emergency-response planning. These tables also show the spatial distribution and extents of the traffic impacts throughout the highway system and, in this way, supplement the information provided in Figures 7-12 through 7-14. The following paragraphs provide an example of how these data can be interpreted in order to gain insights into post-earthquake traffic-impact patterns.

- Tables 7-4 and 7-5 show that this scenario earthquake has the greatest impacts on travel times and trips to/from the Santa Monica, UCLA-Westwood, Encino, and North Hollywood TAZs. These large traffic impacts for the Santa Monica and UCLA-Westwood TAZs would be anticipated, since these are the designated TAZs from Figure 7-5 that are closest to the most severely damaged segments of the I-10 and I-405 freeways.

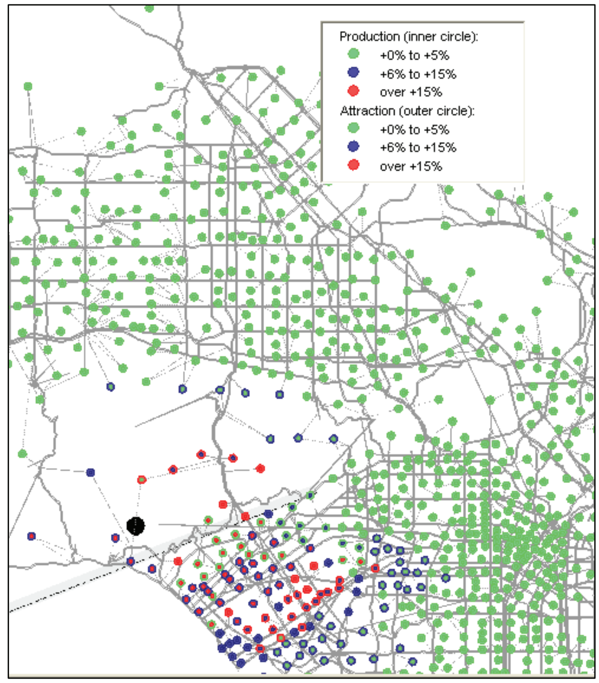
- However, the rather large travel-time and trip impacts for the Encino and North Hollywood TAZs are less intuitive in view of their greater distance from the severely damaged sections of the highway system. Therefore, it is necessary to further examine the data from Tables 7-4 to 7-6 in order to better understand the possible causes of these large impacts.

- For example, Table 7-6 contains earthquake-induced travel-time impacts for user-designated routes in the system. These data show major travel-time increases, not only for the damaged segments of the I-10 and I-405 freeways that are closest to the Santa Monica and UCLA-Westwood TAZs, but also for the I-101 freeway.

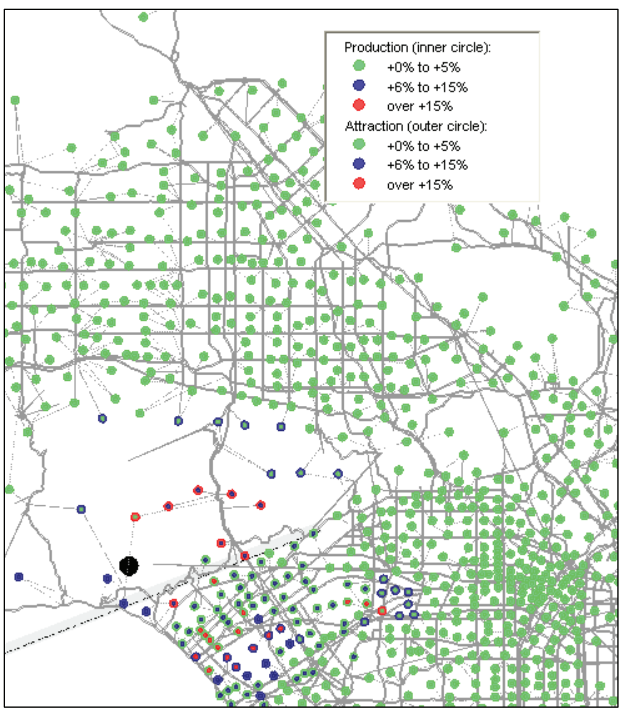
- From this, the following rationale for the above traffic impacts for the Encino and North Hollywood TAZs can be hypothesized: (a) the I-101 freeway parallels the I-10 freeway as a major route into the downtown-LA commercial center, and both of these freeways are heavily traveled; (b) thus, because of the severe damage along the I-10 freeway, many travelers that would ordinarily use that freeway as a route to downtown LA would instead use the I-101 freeway as an alternative route; and (c) because the I-101 freeway was already congested before the earthquake, the additional travelers now taking that route will cause all of the users of I-101 to experience markedly increased travel time delays; and (d) because of this increased congestion along I-101, travelers who previously used that freeway might instead opt to use major arterials or other alternative routes to downtown LA, resulting in a net decrease in the number of trips along I-101 after the earthquake.



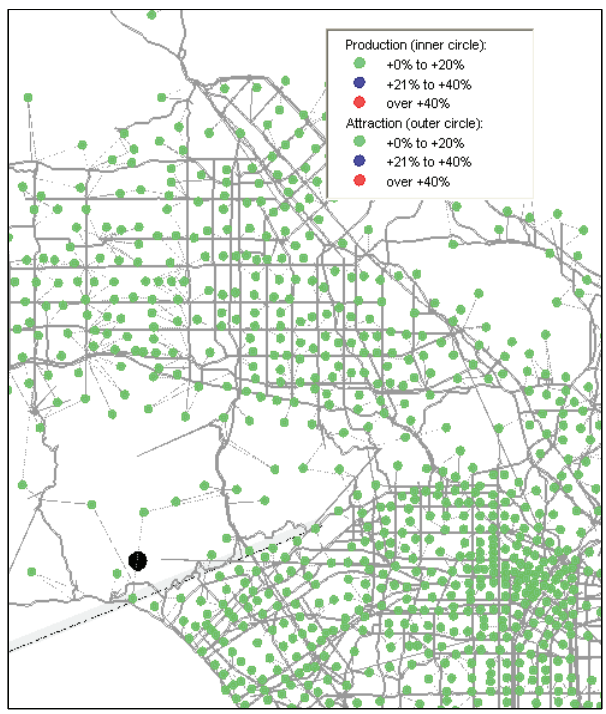
a) 7-Days after Earthquake



b) 60-Days after Earthquake



c) 150-Days after Earthquake



d) 221-Days after Earthquake

Figure 7-14. Post-Earthquake Reductions in Automobile Trips (as percentage of Pre-Earthquake Automobile Trips)

Table 7-4. Post-Earthquake Travels Time Increases for Traffic Analysis Zones shown in Figure 7-5

Traffic Analysis Zone	Post-Earthquake Travel-Time Increases (as percentage of pre-earthquake travel times) *(Note that 0.00% means no change in post-EQ travel time relative to pre-EQ time)*							
	7-Days after EQ		60-Days after EQ		150-Days after EQ		221-Days after EQ	
	Access Time	Egress Time	Access Time	Egress Time	Access Time	Egress Time	Access Time	Egress Time
San Fernando	0.17%	0.00%	0.13%	0.00%	0.13%	0.00%	0.00%	0.00%
Granada Hills	0.24%	0.00%	0.05%	0.00%	0.05%	0.00%	0.00%	0.00%
Chatsworth	1.52%	0.00%	0.51%	0.00%	0.42%	0.00%	0.00%	0.00%
Northridge	1.62%	2.15%	0.25%	0.66%	0.22%	0.66%	0.00%	0.00%
Van Nuys Airport	3.61%	0.00%	0.33%	0.00%	0.33%	0.00%	0.00%	0.00%
Panorama City	0.75%	0.00%	0.05%	0.00%	0.05%	0.00%	0.00%	0.00%
Burbank Airport	4.47%	3.55%	0.18%	0.00%	0.17%	0.00%	0.00%	0.00%
North Hollywood	17.45%	6.88%	0.31%	1.62%	0.31%	1.05%	0.00%	0.00%
Glendale	4.51%	0.00%	1.06%	0.00%	0.90%	0.00%	0.00%	0.00%
Woodland Hills	1.14%	1.37%	1.14%	1.37%	1.14%	1.37%	0.00%	0.00%
Reseda	2.47%	0.91%	0.99%	0.91%	0.93%	0.91%	0.00%	0.00%
Encino	20.12%	4.13%	0.48%	4.13%	0.48%	4.13%	0.00%	0.00%
Santa Monica	0.50%	13.22%	0.50%	8.56%	0.50%	7.27%	0.00%	0.00%
UCLA-Westwood	9.30%	3.56%	9.30%	2.66%	6.38%	2.00%	0.00%	0.00%
Beverly Hills – Wilshire Boulevard	1.47%	4.62%	1.47%	2.23%	1.47%	0.00%	0.00%	0.00%
Downtown LA	0.30%	1.06%	0.30%	1.06%	0.30%	1.06%	0.00%	0.00%
University of Southern CA	0.00%	2.47%	0.00%	2.47%	0.00%	2.47%	0.00%	0.00%
Inglewood	0.10%	3.09%	0.10%	3.09%	0.10%	3.09%	0.00%	0.00%
Los Angeles Airport	1.66%	5.21%	1.66%	5.00%	1.66%	5.00%	0.00%	0.00%

Table 7-5. Post-Earthquake Trips to/from Traffic Analysis Zones shown in Figure 7-5

Traffic Analysis Zone	Post-Earthquake Changes in Trips (as percentage of pre-earthquake trips) *(Note that 0.00% means no change in post-EQ trips relative to pre-EQ trips)*							
	7-Days after EQ		60-Days after EQ		150-Days after EQ		221-Days after EQ	
	From TAZ	To TAZ	From TAZ	To TAZ	From TAZ	To TAZ	From TAZ	To TAZ
San Fernando	-6.10%	-1.58%	-1.63%	0.00%	-1.63%	0.00%	0.00%	0.00%
Granada Hills	-4.87%	-0.84%	-1.07%	0.00%	-1.07%	0.00%	0.00%	0.00%
Chatsworth	-2.95%	-0.82%	-0.67%	0.00%	-0.67%	0.00%	0.00%	0.00%
Northridge	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Van Nuys Airport	-7.94%	-1.25%	-1.86%	0.00%	-1.86%	0.00%	0.00%	0.00%
Panorama City	-6.00%	-1.40%	-0.97%	0.00%	-0.86%	0.00%	0.00%	0.00%
Burbank Airport	-7.88%	-2.76%	-0.95%	0.00%	-0.95%	0.00%	0.00%	0.00%
North Hollywood	-15.76%	-13.23%	-0.70%	-0.10%	-0.70%	-0.06%	0.00%	0.00%
Glendale	-6.46%	-6.48%	-0.62%	-0.44%	-0.62%	-0.31%	0.00%	0.00%
Woodland Hills	-7.63%	-8.50%	-0.46%	0.00%	-0.24%	0.00%	0.00%	0.00%
Reseda	-9.82%	-5.83%	-0.97%	0.00%	-0.74%	0.00%	0.00%	0.00%
Encino	-32.60%	-21.34%	-2.40%	-0.17%	-2.18%	-0.03%	0.00%	0.00%
Santa Monica	-11.02%	-37.96%	-5.39%	-26.08%	-2.90%	-18.44%	0.00%	0.00%
UCLA-Westwood	-6.71%	-30.63%	-5.49%	-12.54%	-0.25%	-4.66%	0.00%	0.00%
Beverly Hills – Wilshire Boulevard	-3.48%	-9.69%	-1.69%	-3.30%	-1.50%	-1.35%	0.00%	0.00%
Downtown LA	-6.69%	-5.80%	-2.11%	-0.77%	-1.14%	-0.56%	0.00%	0.00%
University of Southern CA	-3.50%	-2.61%	-1.00%	-0.49%	-0.17%	-0.33%	0.00%	0.00%
Inglewood	-3.28%	-3.03%	-0.47%	-1.53%	0.00%	-1.04%	0.00%	0.00%
Los Angeles Airport	-6.72%	-1.97%	-1.03%	-1.72%	-1.03%	-1.72%	0.00%	0.00%

Table 7-6. Post-Earthquake Travel Times along Key Routes shown in Figure 7-6

Key Route	Post-Earthquake Travel-Time Increases (as percentage of pre-earthquake travel times)			
	7-Days after EQ	60-Days after EQ	150-Days after EQ	221-Days after EQ
(a) I-5 (Golden State Freeway) from San Fernando to Burbank (pre-EQ travel time = 13.1 minutes)	16.30%	1.41%	0.88%	0.00%
(b) I-5 (Golden State Freeway) from Burbank to downtown LA (pre-EQ travel time = 13.9 minutes)	2.31%	1.67%	1.96%	0.00%
(c) I-405 (San Diego Freeway) from I-5 to I-10 Interchange (pre-EQ travel time = 37.0 minutes)	125.60%	34.61%	34.38%	0.00%
(d) I-405 (San Diego Freeway) from I-10 Interchange to LA Airport (pre-EQ travel time = 19.0 minutes)	134.00%	63.56%	3.04%	0.00%
(e) I-10 (Santa Monica Freeway) from Santa Monica to downtown LA (pre-EQ travel time = 18.1 minutes)	209.73%	91.37%	37.57%	0.00%
(f) I-110 (Harbor Freeway) from I-105 to downtown LA (pre-EQ travel time = 9.7 minutes)	-0.38%	-1.59%	-2.56%	0.00%
(g) I-101 (Ventura/Hollywood Freeway) from I-405 to downtown LA (pre-EQ travel time = 30.5 minutes)	108.35%	1.18%	0.89%	0.00%

7.3.6 ECONOMIC LOSSES

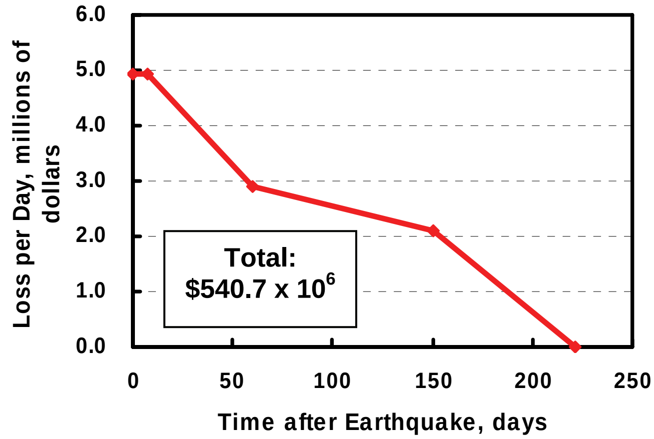
The REDARS™ 2 estimates of economic losses due to the earthquake damage to the LA-testbed highway system include repair costs, and losses due to travel-time delays and trips foregone. The repair costs are estimated by applying the default bridge, approach-fill, pavement, and tunnel models that are described in Appendices G and H of this report.

The losses due to travel-time delays and trips foregone will depend on the post-earthquake traffic impacts estimated by the REDARS™ 2 network analysis procedure that is described in Chapter 5 and Appendix I. These traffic impacts are computed for each of the four post-earthquake times that are input by the user. Therefore, the losses due to travel-time delays and trips foregone are estimated as dollar losses per day at each post-earthquake time. For this analysis, these losses as estimated at times of 7-, 60-, 150-, and 221-days after the earthquake are shown in Table 7-7.

Table 7-7. Economic Losses due to Travel-Time Delays and Trips Foregone

Time after the Earthquake	Loss per Day, Millions of Dollars
0-7 days	$4.90
60 days	$2.89
150 days	$2.11
221 days (system recovery time)	$0.00

a) Loss per day



b) Computation of Total Loss from Travel-Time Delays and Trips Foregone

After these losses per day are estimated, they are plotted vs. time after the earthquake, as shown above. Then, the total economic loss due to travel-time delays and trips foregone is computed as the area under the resulting curve of loss/day vs. post-earthquake time. As shown in Table 7-7, this turns out to be $540.7 million-dollars. Finally, this loss is added to the damage repair costs in order to estimate the total economic loss due to this scenario earthquake. These results are shown in Table 7-8. This table shows that the economic loss due to travel-time delays and trips foregone are over twice as large as the repair costs.

Table 7-8. Estimated Total Economic Loss due to this Scenario Earthquake

Type	Loss, Millions of Dollars
Repair Cost	$255.4
Total Loss from Travel-Time Delays and Trips Foregone	$540.7
Total	$796.1

7.4 PROBABILISTIC ANALYSIS

A key feature of the REDARS™ 2 methodology is its ability to carry out probabilistic as well as deterministic analysis of a highway system. These probabilistic analyses can be: (a) conditionally probabilistic (e.g., an analysis for a single fixed earthquake event in which uncertainties in estimating seismic hazards and component damage states are considered); or (b) fully probabilistic (in which uncertainties in earthquake occurrence as well as seismic-hazard and component damage estimates are considered). Appendix K of this report provides an example of a conditional probabilistic application of REDARS™ 2 that was used to calibrate the REDARS™ 2 default bridge model against bridge-damage observations from the Northridge Earthquake.

The remainder of this section focuses on fully probabilistic applications of REDARS™ 2. It contains two parts. The first part describes the various types of probabilistic output that REDARS™ 2 can provide. The last part of this section describes convergence checks that have been built into REDARS™ 2 to enable the user to assess when, at some intermediate number of walkthrough years, the confidence intervals for the results are sufficient to justify termination the probabilistic analysis at that point.

7.4.1 PROBABILISTIC OUTPUT

REDARS 2 provides various types of probabilistic that can be used to characterize the seismic performance of the highway system, the seismic performance of individual components within the system, and seismic hazards at specified locations within the system.

7.4.1.1 Characterization of Seismic Performance of Overall Highway System

REDARS™ 2 provides the following four types of output for use in characterizing the seismic performance of a highway system:

- ***Economic Losses.*** REDARS™ 2 computes economic losses as the sum of the costs/losses due to the following effects of earthquake-induced damage to the highway system: (a) costs to repair the damaged highway-roadway infrastructure (e.g., App. C and D); (b) consequences of system-wide travel-time delays caused be earthquake damage to the system (Chap. 6); and (c) effects of trips foregone due to increased congestion caused this earthquake damage. Figure 7-15 shows probabilistic estimates of economic losses developed during this LA-area demonstration application. Subsection 7.4.2 illustrates how these probabilistic results can be used in benefit-cost assessments of alternative seismic-risk-reduction strategies.

- ***Travel Times to Key Locations.*** In addition to economic losses, other measures of the seismic performance of the highway system may be relevant. One such measure is how travel times to key locations (such as medical centers, airports, etc.) may be affected by earthquake damage to the system. For example, Figure 7-16 provides probabilistic estimates of travel times to the UCLA-Westwood area of LA, where a major medical center is located, and in addition, is the site of a large university and a center of commerce.

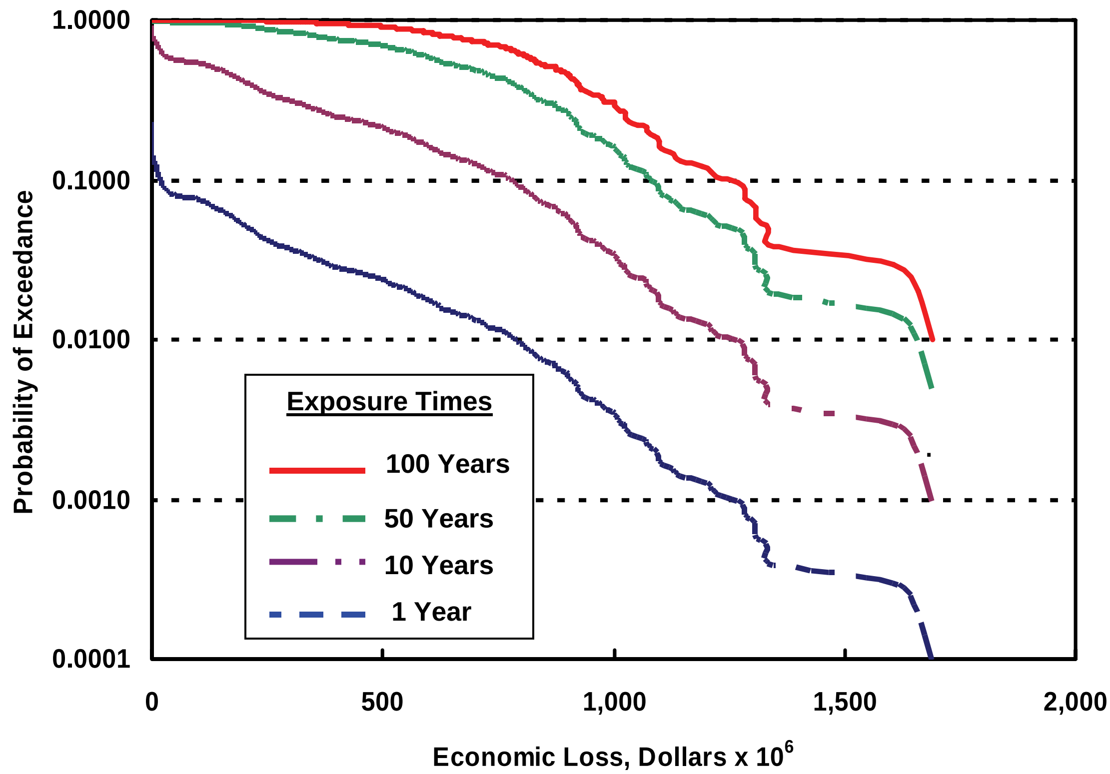
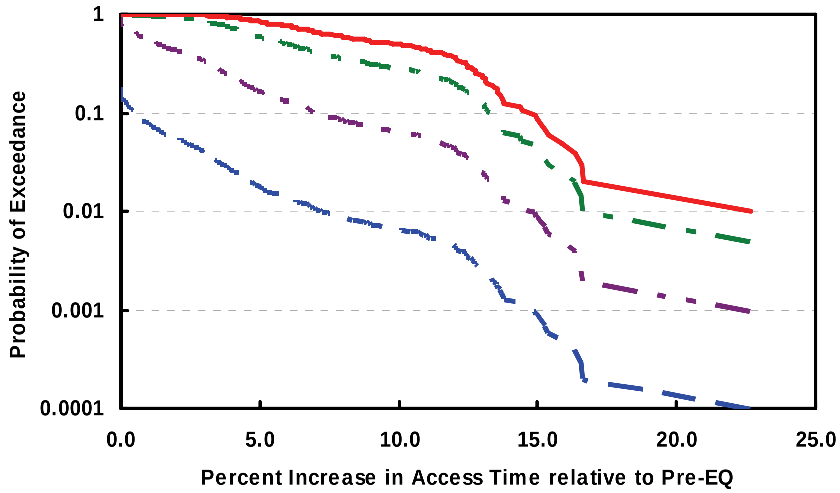


Figure 7-15. Economic Losses

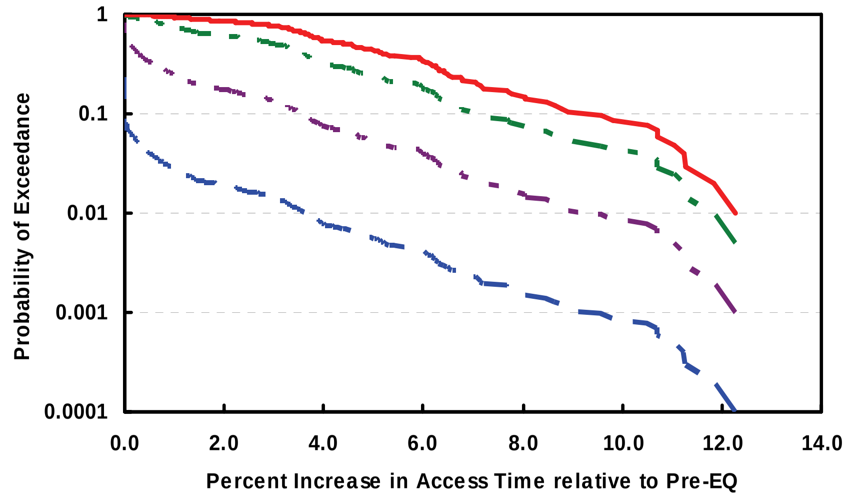
- ***Travel Times along Key Routes.*** Certain routes in an earthquake-prone region may be designated as "lifeline routes", which means they must remain functional to carry emergency traffic after an earthquake. In addition, certain routes will be important for travel to/from a key location after an earthquake. Figure 7-17 displays probabilistic estimates of travel time delays along I-405 between I-10 and I-105 (route (d) in Fig. 7-6), which is an important link to/from the LA International Airport.[6]

- ***Trips to/from Key Locations***. Another possible impact of earthquake damage to a highway system is its effect on trips to/from key locations in a region. For example, if trips to a major center of commerce are substantially reduced, this could be an indicator of possible losses of customers (and revenues) to merchants in that area. Also, if trips from a center of manufacturing that provides machinery or equipment to businesses in the region (or beyond the region), this could represent losses of revenue not only to the manufacturers, but also to the businesses that depend on shipments from these manufacturers. Figure 7-18 displays probabilistic estimates of reductions in trips to downtown LA.

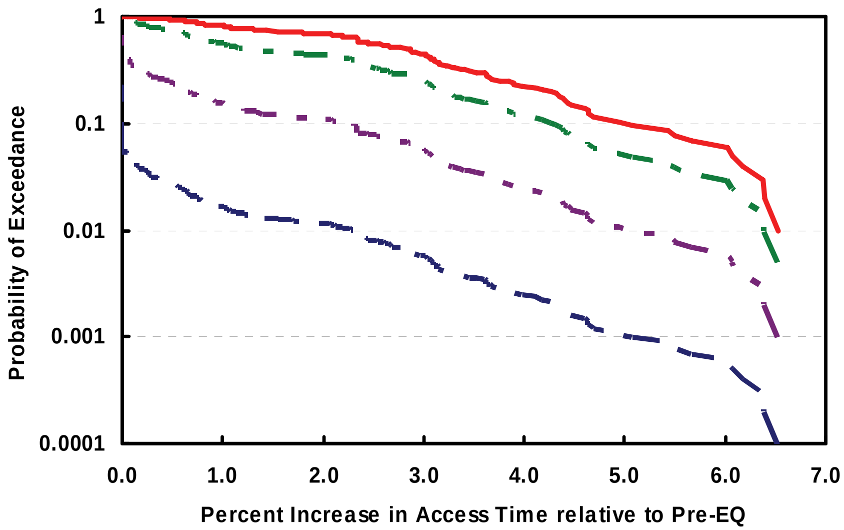
[6] Figure 7-17 shows that, in some cases, there may a slightly negative increase in travel times along these routes (which is actually a travel-time decrease). This can occur when effects of reductions in trips along the route exceed the effects of travel-time increases due to actual damage to the segment. For example, reductions in these trip demands along I-405 to the south of I-10 could be related to the damage to I-405 to the north (Sunset Boulevard and I-10 area).



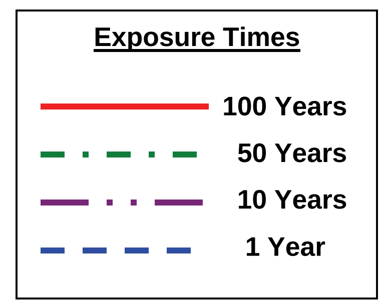
a) Time after EQ = 7-Days



b) Time after EQ = 60-Days

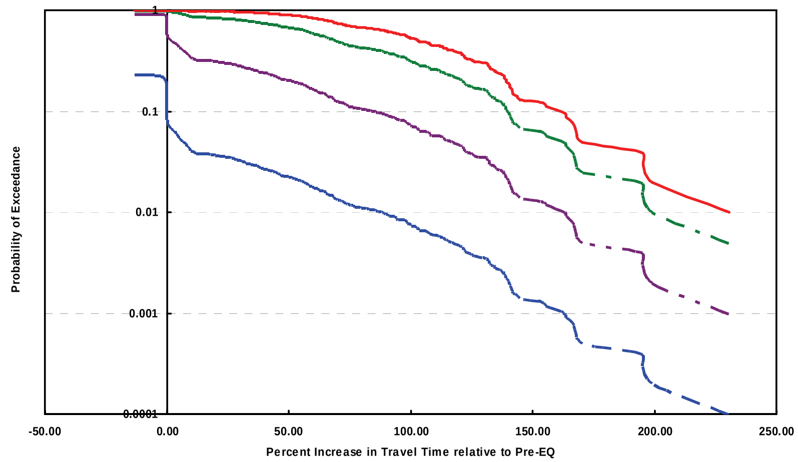


c) Time after EQ = 150-Days

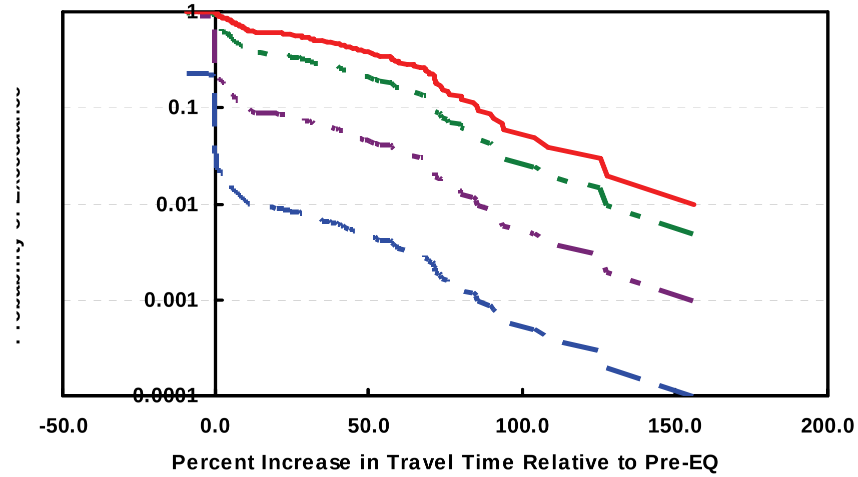


Note: At 221-days after EQ, system returns to pre-EQ state (percent increase in travel time = 0.0)

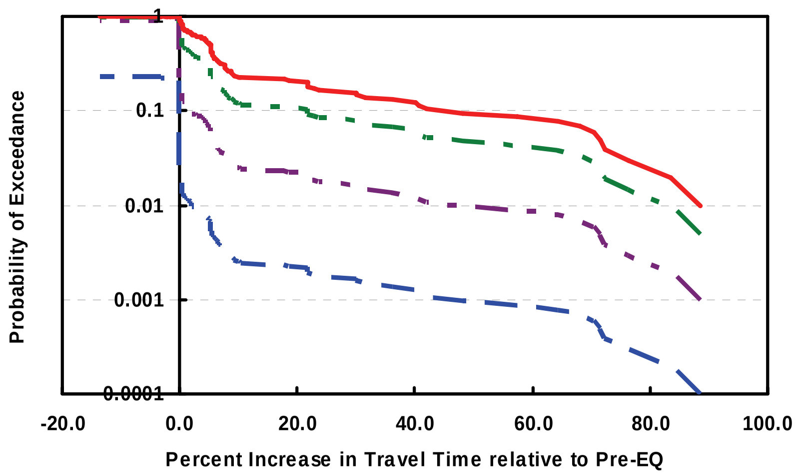
Figure 7-16. Percent Increase in Access Times to UCLA Medical Center



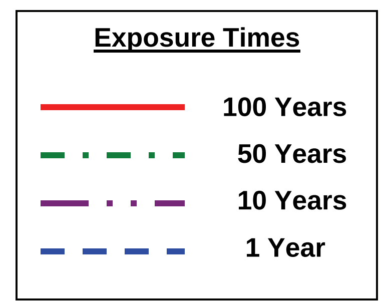
a) Time after EQ = 7-Days



b) Time after EQ = 60-Days



c) Time after EQ = 150-Days



Note: At 221-days after EQ, system returns to pre-EQ state (percent increase in travel time = 0.0)

Figure 7-17. Percent Increase in Travel Time along I-405 between I-10 and I-105 (Key Route to LA International Airport)

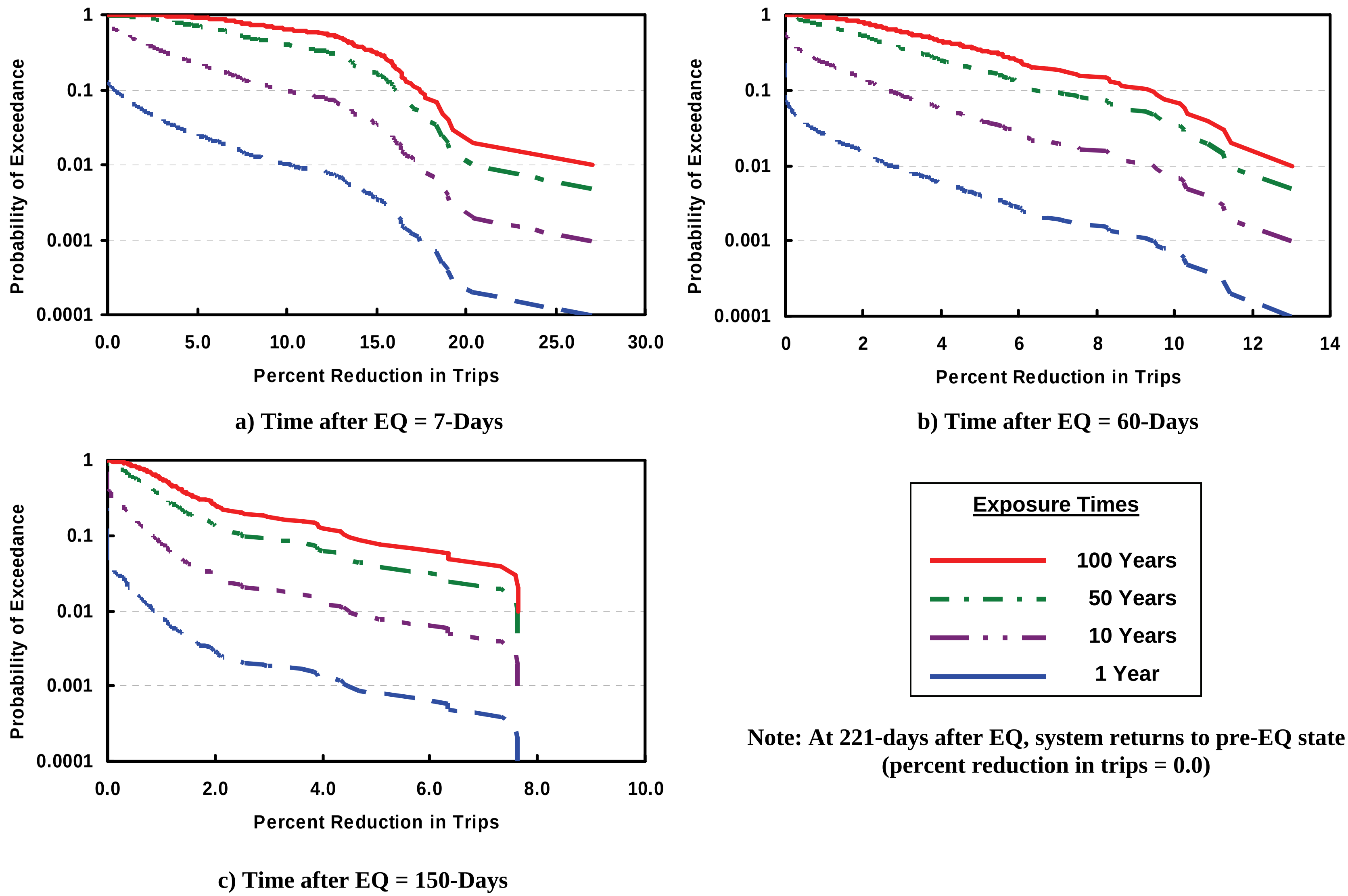


Figure 7-18. Percent Reduction in Trips to Downtown LA

In closing, the preceding figures illustrate that REDARS™ 2 results can to enable users to more directly consider a broad range of highway-system performance measures that could relate to economic losses to the surrounding region. For example, such considerations could be an impetus for the future development of region-specific criteria for performance-based design of new components along a highway system (e.g., Buckle 2003). They could also be important for assessing various options for seismic-risk reduction of existing components (e.g., see Sec. 7.5). Further development of such methods to consider system-performance measures in seismic-risk-reduction planning and criteria will be addressed in future projects that focus on the continued upgrading and development of the REDARS™ SRA methodology and software.

7.4.1.2 Characterization of Seismic Performance of Individual Components of Highway System

For highway system components, REDARS™ 2 can provide probabilities that a given component will be in the minor, moderate, extensive, and collapse damage states, as defined in Chapter 4. These probabilistic representations of component damageability incorporate effects of uncertainties in earthquake occurrence, and in the estimation of site-specific seismic hazards and component damage states. Therefore, this provides a much more complete picture of the vulnerability of a component than do more conventional component vulnerability representations in which effects of these uncertainties are not considered.

Figure 7-19 illustrates one type of display of system-wide component-damage probabilities -- which is in the form of a map of the LA-testbed highway system that shows the each bridge's probability of collapse. This display of bridge-collapse probabilities can be useful during overall planning of bridge seismic-upgrade programs, by identifying those bridges within the highway system that are most vulnerable. Use of this information, along with REDARS™ SRA results that indicate each bridge's importance to overall system-wide traffic flows, provides an improved basis for establishing bridge-retrofit priorities.[7]

Figures 7-20 and 7-21 show how REDARS™ 2 can also display bridge-damage probabilities for a single bridge in the system. Both figures contain bar charts that show probabilities that a given bridge will be in each of the discrete damage states that is currently considered in REDARS™ 2 (i.e., the minor, moderate, major, and collapse damage states). Figure 7-20 provides side-by-side bar charts for two different bridges in the LA-testbed system with differing levels of vulnerability. Such side-by-side comparisons of bar charts for different bridges clearly show at a glance the relative vulnerabilities of various bridges in the highway system.

These bar charts can also be used to assess effects of seismic retrofit of a given bridge. Figure 7-21 provide such results for a single bridge in the LA-area highway system that has been retrofitted, which clearly show the benefit of this retrofit in substantially reducing the probability of collapse.

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[7] REDARS™ 2 is not yet able to provide system-wide bridge-collapse probability maps of the type shown in Figure 7-19. However, this inclusion of such maps will be a high priority task in the next set of future enhancements of REDARS™ that are now being planned.

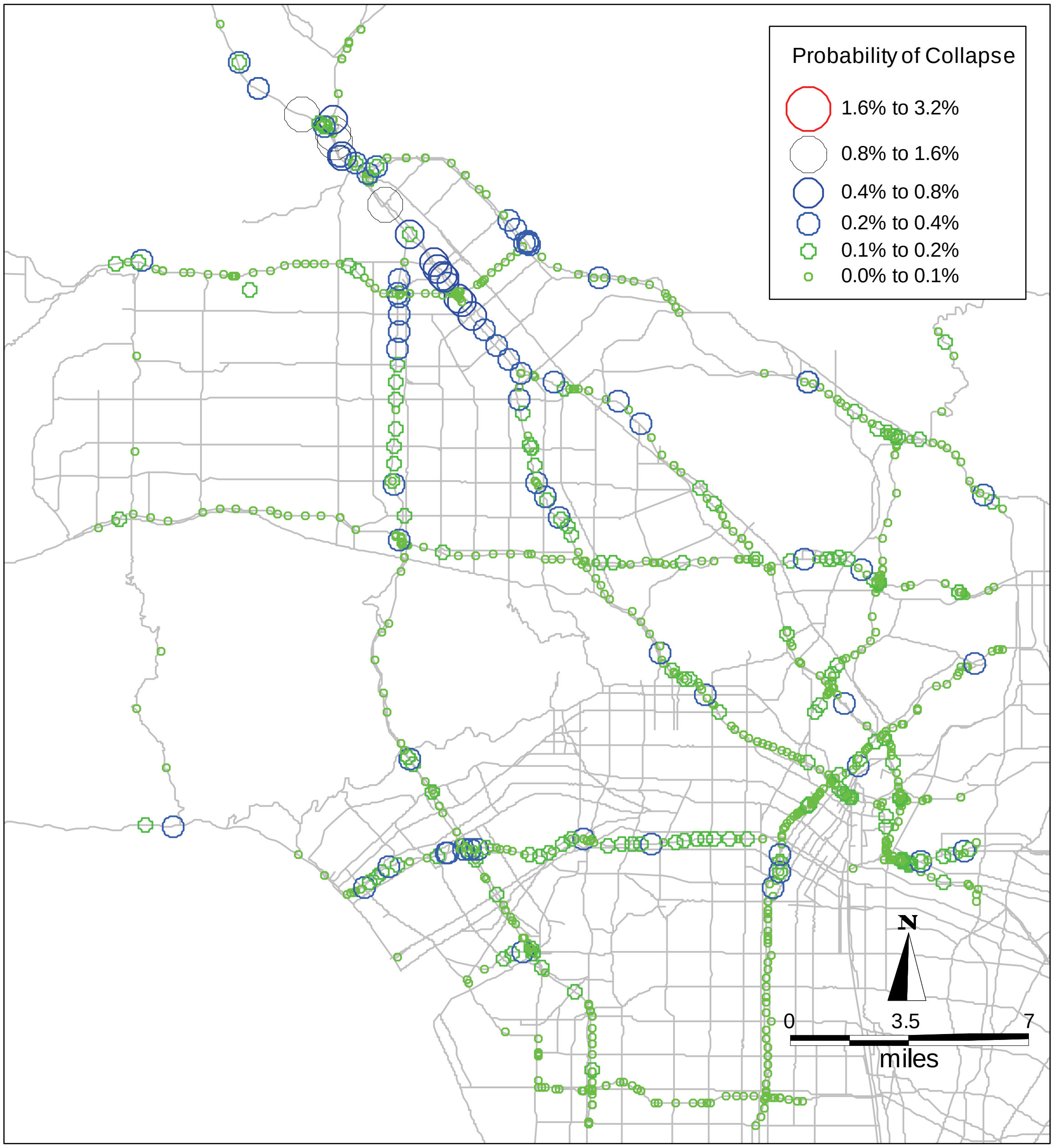

Figure 7-19. LA-Area Highway System Map showing Those Bridges with the Highest Probability of Collapse

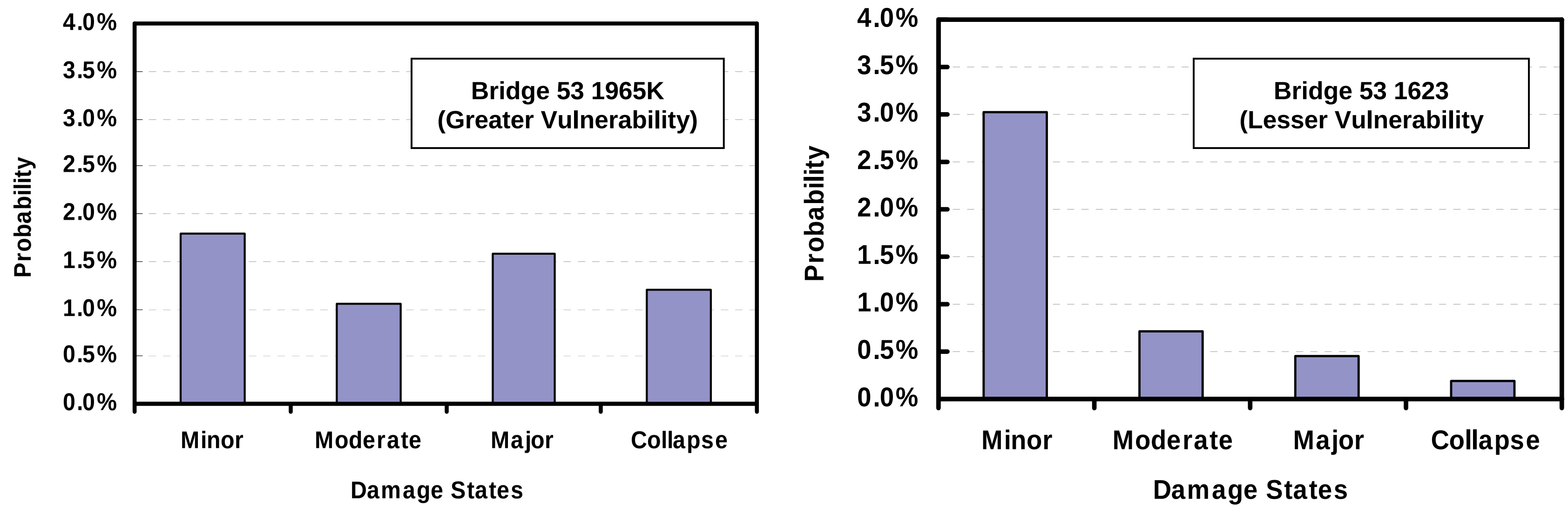

Figure 7-20. Probability Bar Charts for Bridges with Different Degrees of Vulnerability

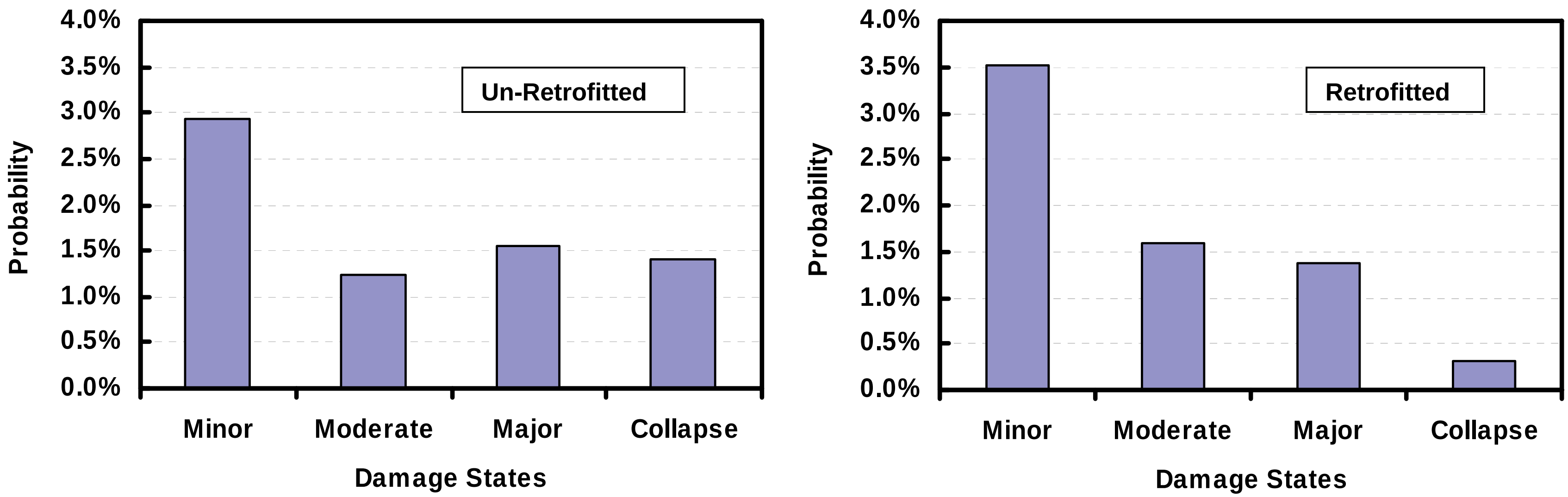

Figure 7-21. Probability Bar Charts for Unretrofitted and Retrofitted Bridge 53 1984L

7.4.1.3 Characterization of Uncertainties in Ground Motions

REDARS™ 2 can develop probabilistic estimates of the intensity of the ground motions at any site in the system, where ground motions are characterized in terms of peak ground acceleration or spectral accelerations at periods of 0.3 sec. or 1.0 sec. These estimates are provided as plots of probability of exceedance vs. ground-motion level at four different user-specified exposure times. Figure 7-22 provides an example set of probability estimates for spectral accelerations at a period of 1.0 sec. at Bridge 53-1318 in this testbed roadway system.

As the number of simulations increases, these probabilistic ground-motion estimates from REDARS™ 2 will tend to converge to estimates developed from conventional seismic-hazard-analysis methods that use the same ground-motion attenuation model and earthquake model as in the REDARS™ 2 analysis. Thus, a user can check any set of REDARS™ 2 probabilistic ground-motions estimates by performing an independent seismic-hazard-analysis with the same models.

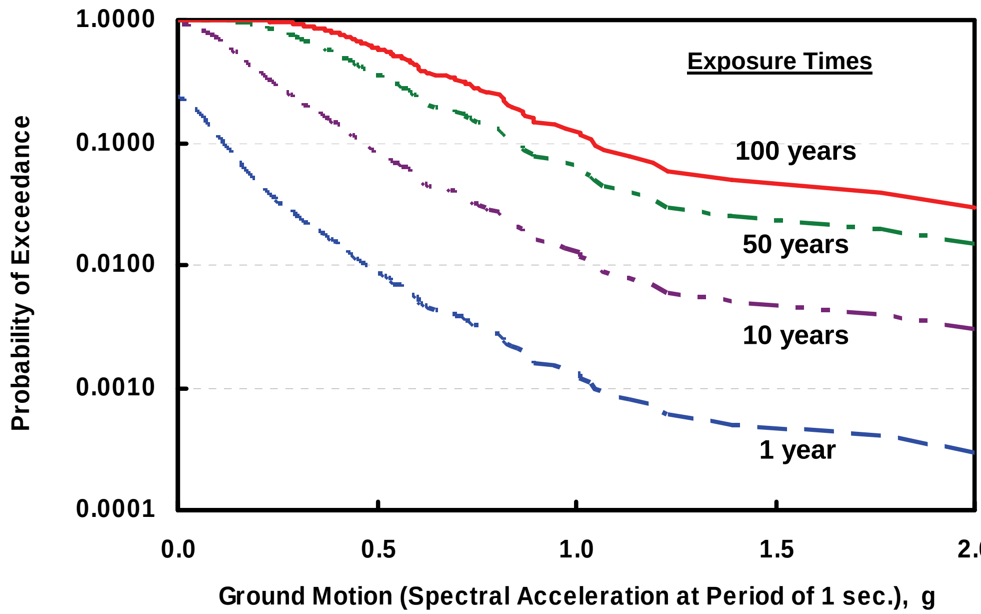

Figure 7-22. REDARS™ 2 Probabilistic Ground Motion Estimates at Bridge 53 1318 in LA-Testbed Highway System

7.4.2 CONVERGENCE CHECKS

7.4.2.1 Background

As described in Chapter 2, the REDARS™ 2 SRA methodology and software use a Monte Carlo process to develop statistically sound probabilistic SRA results. REDARS™ also includes a check of statistical confidence intervals in the AAL results as the analysis proceeds through successive damaging earthquake scenarios contained in the walkthrough table. If the REDARS™ 2 user judges that an acceptable confidence interval has been achieved after some intermediate number of damaging earthquake scenarios has been considered, he/she can terminate the SRA at that stage of the analysis. This could result in significant reductions in the computer time needed to carry out the SRA, relative to the time that would be needed if SRA results were developed for all of the damaging earthquakes contained in the walkthrough table. To facilitate this check of convergence intervals, an advanced and efficient statistical analysis procedure – named the variance-reduction method – has been developed under this project and programmed into REDARS™ 2. This method is described in Appendix J.

The probabilistic SRA of the LA-testbed highway system that is described in Section 7.4 was carried out for all of the 2,645 damaging earthquakes that occurred throughout the overall 10,000-year duration of the earthquake walkthrough table (see Section 7.2.6). When the analysis was completed for each successive earthquake, updated confidence intervals were computed and stored. Section 7.4.2.2 shows how these confidence intervals converged as the analysis proceeded through each year of the walkthrough table.

7.4.2.2 Results

This convergence check estimated 95-percent confidence intervals. That is, these confidence intervals are represented by the term X, in the following statement: "there is a 95-percent confidence that the computed value of the AAL is within ±X-percent of the true value."

Two forms of results were developed in this convergence check. The first, which is shown in Figure 7-23a, is in the form of a "funnel test" which visually shows how the confidence interval about the computed and "true" values of the AAL improve as the number of walkthrough years increases. In this, the "true" value of the AAL was assumed to correspond to the value that resulted when the entire 10,000 year walkthrough was completed.

The second set of results, which are provided in Figure 7-23b, show the actual value of the 95-percent confidence interval, as a function of the number of walkthrough years processed. These results show that, if only about 2,500 of the 10,000 walkthrough years is considered, the 95-percent confidence interval is less than 10 percent. For most situations, this would be acceptable, and if the AAL is to be the basis for checking the confidence intervals in the REDARS™ 2 results, the SRA could be terminated at that time. This would result in a substantial reduction in the computer time needed to carry out this SRA.

However, it is noted that parameters other than or in addition to the AAL may be relevant to the user and, if so, confidence intervals in these results will differ from those developed here for the AAL. For example, if fractile values of the economic losses are relevant, a larger number of walkthrough years would need to be considered in order to obtain a given confidence interval. The development of confidence intervals for such other parameters will be addressed under future projects that further develop and upgrade the REDARS™ SRA methodology and software (see Chapter 8)

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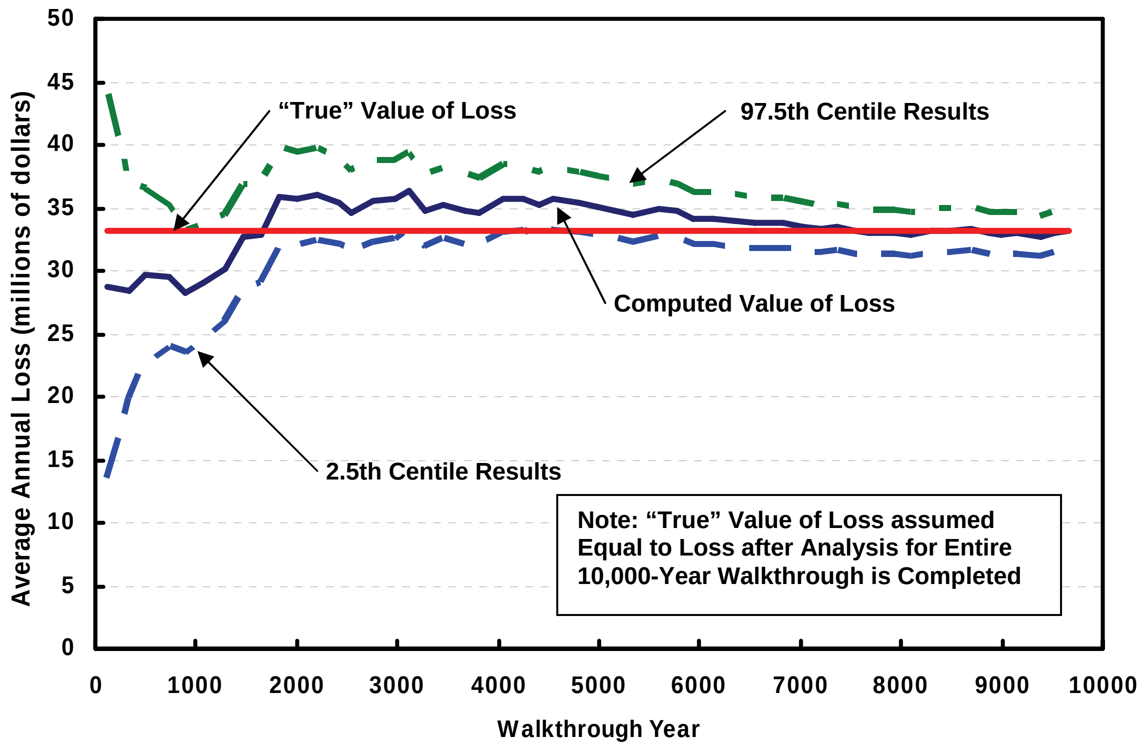
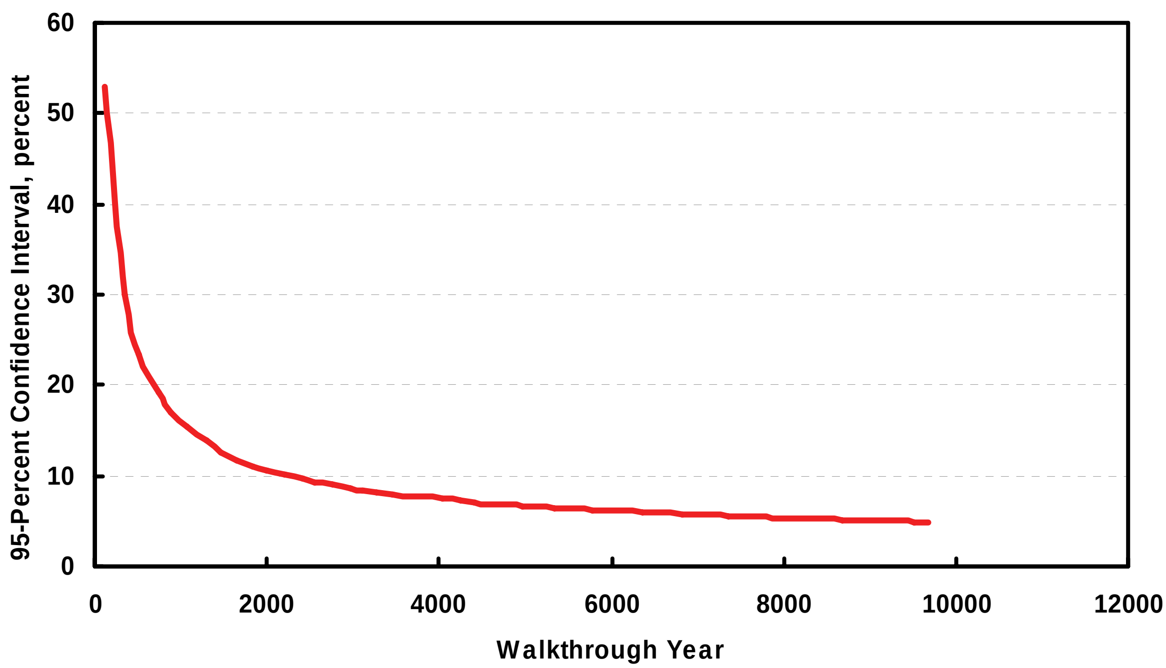


a) Funnel Test



b) 95-Percent Confidence Interval vs. Number of Walkthrough Years Considered

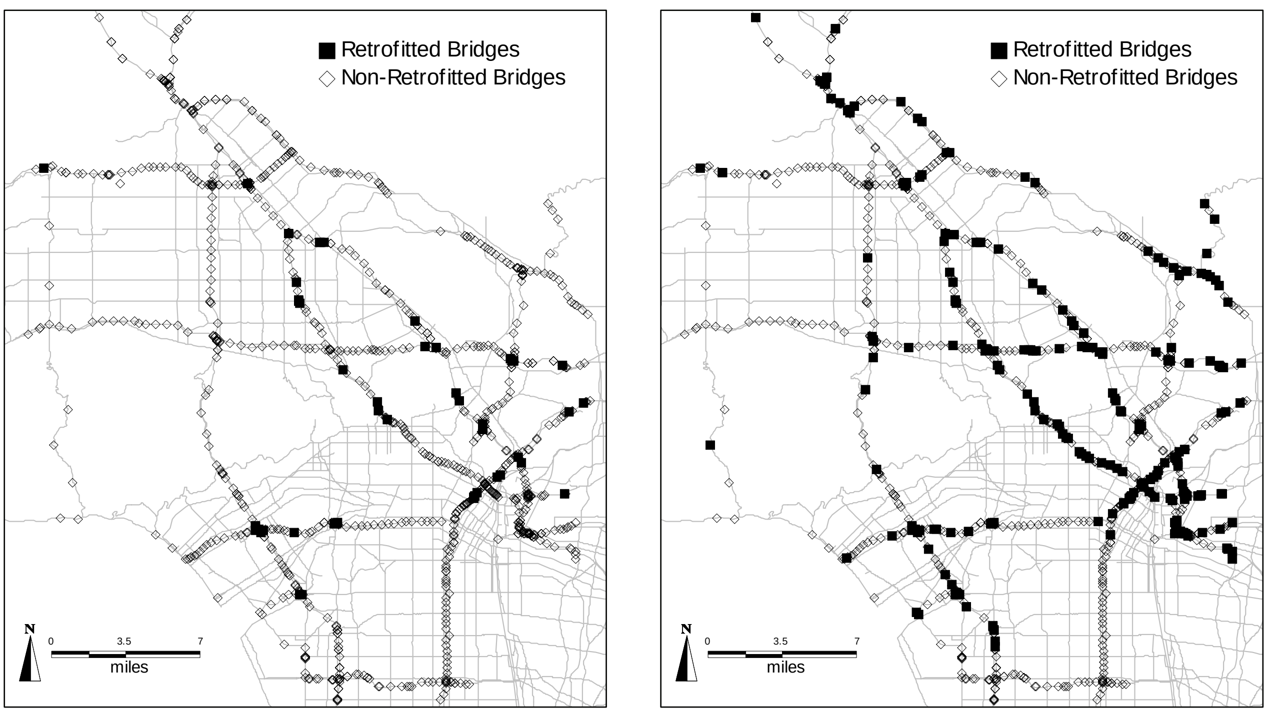
Figure 7-23. Confidence Intervals for Results of Probabilistic SRA of LA-Testbed System

7.5 EXAMPLE ECONOMIC ANALYSIS OF A BRIDGE RETROFIT PROGRAM

7.5.1 BACKGROUND

This section provides an example application of REDARS™ 2 that shows how its probabilistic estimates of economic losses (Sec. 7.4.1.1) can facilitate seismic-risk-reduction decision making. In this example, these probabilistic loss estimates are used in an evaluation of the economic viability of a series of actual bridge seismic retrofits in the grater LA area that have been completed, as part of a major bridge-retrofit program that has been carried out throughout much of the state of California.

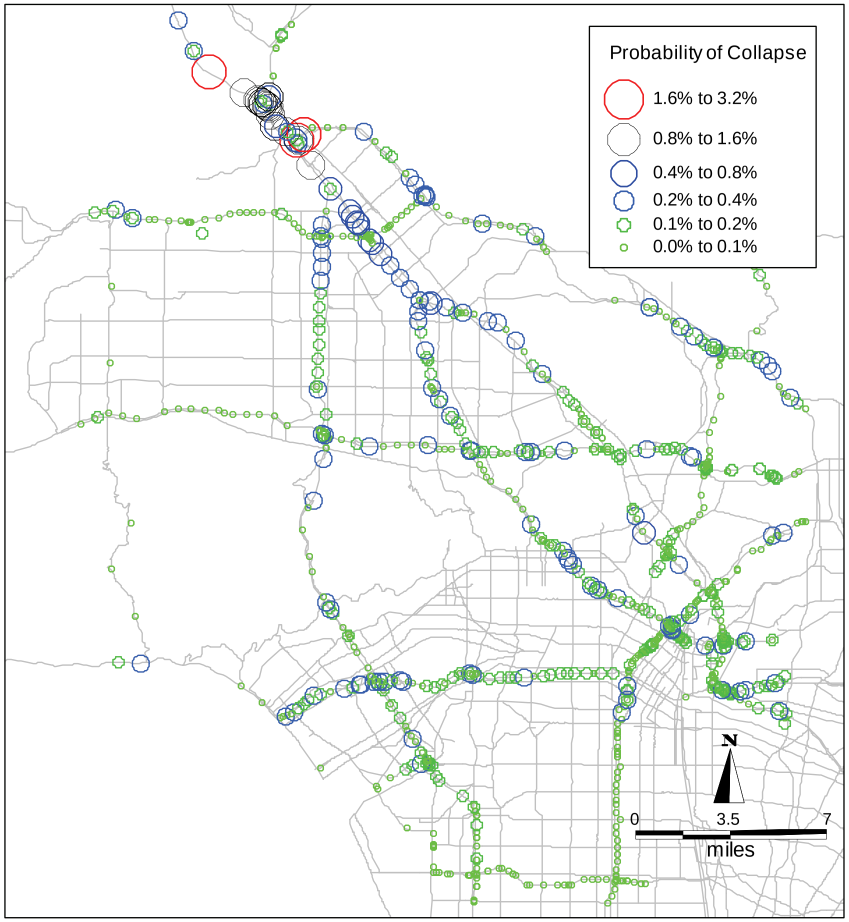
This economic analysis considers only those bridges that are located in the LA-testbed highway system and, in addition, only those bridge retrofits that have been carried out within this system since the 1994 Northridge Earthquake and up to the end of 2004. Within this system, 57 bridges had been column jacketed prior to this earthquake. After the Northridge Earthquake, and through the end of 2004, an additional 231 bridges within the testbed system were column jacketed -- resulting in a total of 288 column-jacketed bridges in the system as of the end of 2004 (Yashinsky 2005). Figure 7-24 shows the locations of the retrofitted bridges throughout the LA-testbed system, before and after these additional 231 bridge retrofits were completed, and Figure 7-25 provides probabilistic estimates of bridge collapses throughout the highway system with and without the additional bridge retrofits. This figure shows how these retrofits have reduced the estimated probabilities of bridge collapse throughout this system



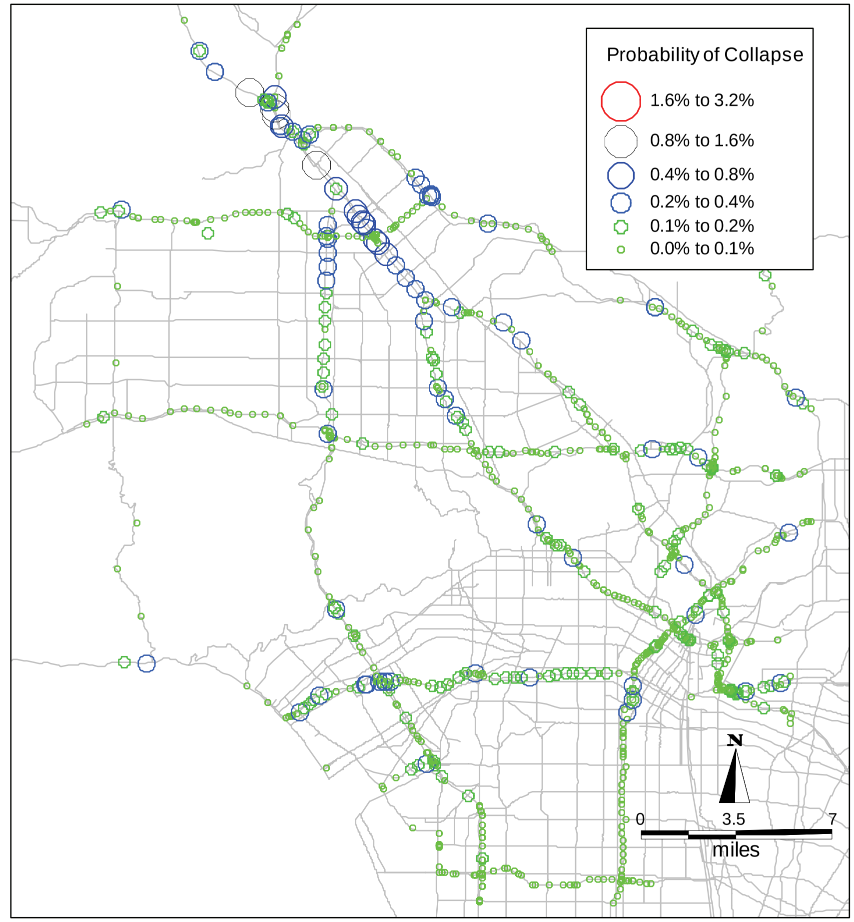
a) System Prior to Northridge Earthquake (early 1994)

b) System as of End of 2004

Figure 7-24. Column-Jacketed Bridges in LA Testbed Highway System



a) As of Early 1994, shortly after Northridge Earthquake



b) As of end of 2004

Figure 7-25. Maps showing Probabilities of Collapse of Bridges throughout LA Testbed Highway System

7.5.2 SUPPOSITIONS

This example analysis examines the economic viability of carrying out these additional 231 bridge retrofits. It is based on the following suppositions.

- It is the year 1994 just after the Northridge Earthquake, when only 57 of the bridges in the testbed system had been column-jacketed. Following this earthquake, a program to column-jacket an additional 231 bridges in the LA-testbed system has been proposed.
- Members of Caltrans' staff have been asked to assess the economic viability of this proposal, and specifically how much these 231 bridge retrofits might reduce economic losses due to earthquake-induced damage and resulting losses due to increased traffic congestion of this testbed system.
- REDARS™ 2 was available at that time, and was to be used to support this assessment.
- The staff used the economic analysis procedure described in the remainder of this section.

7.5.3 ANALYSIS APPROACH

This economic analysis consisted of: (a) estimation of the costs to carry out the column-jacketing retrofit of these 231 bridges; (b) estimation of the benefits of these retrofits, in reducing losses due to earthquake damage to the testbed highway system, with and without the 231 bridge retrofits; and (c) estimation of the standard deviation of these losses, also with and without the 231 retrofits. These steps are described below.

7.5.3.1 Estimation of Retrofit Costs

The costs of these retrofits were estimated from data provided by Caltrans (Bailey 2005; Yashinsky 2005), according to the following steps:

- The Caltrans bridge–retrofit program has led to the column jacketing of 625 of the 2,267 bridges in the LA area. The total cost of these retrofits was on the order of $300,000,000. This results in an average retrofit cost per bridge of $300,000,000/625 = $480,000.
- From this, the cost to retrofit the 231 bridges under consideration here is estimated to be $480,000. x 231 = $110,880,000. In this analysis, this was rounded off to $111,000,000.

7.5.3.2 Estimation of Reduction of Losses due to Bridge Retrofits

This step involved computation of the present value of the economic losses, over an appropriate exposure time. A range of different discount rates were used in these calculations (where the discount rate is defined as the difference between the rate charged to borrow money and the inflation rate). The following calculations comprised this step:

- Use REDARS™ 2 to perform a probabilistic SRA of the LA-testbed system as of early 1994, when none of the 231 bridge retrofits had yet been carried out (Fig. 7-25a). From the results of this analysis, obtain the average annualized loss (AAL_{1994}) and the standard deviation of the losses (σ_{1994}) from this SRA.

- Use REDARS™ 2 to perform a probabilistic SRA of the upgraded LA-testbed system as of late 2004, when the 231 bridge retrofits are in place (Fig. 7-25b). From the SRA results, obtain the AAL and the standard deviation of the losses (AAL_{2004} and σ_{2004}.respectively).

- Compute the difference between the AALs for these two cases as $\Delta_{AAL} = AAL_{1994} - AAL_{2004}$.

Use Equation 7-1 to compute the present value of this loss difference *PVL* for an exposure time *T* and a discount rate *j*. This value of PVL represents the assumed benefit of the retrofit of these 231 bridges in this demonstration application. As described below, this example includes computations of *PVL* for a range of plausible exposure times and discount rates.

$$PVL = \left[\frac{1-(1+j)^{-T}}{j} \right] * \Delta_{AAL} \qquad (7\text{-}1)$$

7.5.3.3 Computation of Benefit-Cost Ratio

Caltrans' costs to carry out these 231 bridge retrofits between 1994 and 2004 can be viewed as an investment in seismic-risk reduction. To decide whether this investment is sound, one would first assess its potential for providing a good equivalent financial yield. In this example, this measure of the investment's financial-yield potential was represented by the ratio of the potential benefits of the investment (assumed here to correspond to the parameter *PVL* as computed above) to the cost of the investment (which, in this example, is represented by the retrofit cost of $111,000,000 as computed in Section 7.5.3.1).

7.5.3.4 Computation of Standard Deviation of Losses

When evaluating whether to proceed with an investment, a prudent investor would also evaluate its potential volatility; i.e., whether the investment is overly risky. In this example, the volatility of Caltrans' investment in the retrofit of these 231 bridges is represented by the standard deviation of the losses for each simulation of the 10,000 year walkthrough; i.e., as the standard deviation decreases, the volatility/riskiness of an investment in the retrofit of these bridges can also be assumed to decrease.

7.5.4 RESULTS

7.5.4.1 Benefit-Cost Ratio

The exposure times used in these benefit-cost calculations were based on estimated bridge design lives. Since this analysis is for a California highway system, we considered estimated design lives for California, bridges, which Caltrans typically assumes to be about 75 years (Yashinsky, 2005). To bracket this estimate, exposure times of 50-, 75-, and 100-years were used in this analysis. In this, it is assumed that the trip demands provided by SCAG for use in this demonstration analysis will be valid throughout all of these various exposure times, which will not be the case. However, it is expected that trip demands on the LA-testbed highway system will actually during these extended exposure times, and will be larger than these SCAG trip demands. This will actually increase the benefit of the seismic retrofit of the additional 231 bridges over and above the values shown below. Hence, these computed benefit-cost ratios are expected to be conservative (i.e., lower bound estimates) of the ratios that would be computed if actual trip demands for these extended exposure times could be provided.

Discount rates of 2.5, 4, and 7 percent are used in this analysis. Discount rates on the order of 2.5 and 4 percent have been common in recent years and are probably most representative of current values. Previously, discount rates of about 7 percent have been most representative.

Table 7-9 shows the benefit-cost ratios that have been computed on this basis. This table shows benefit-cost ratios of about 2.4 for the older discount rate of 7 percent, and much higher benefit-cost ratios (ranging from about 3.2 to 4.7) when the more current discount rates of 2.5 and 4 percent are used. These results indicate that the retrofit of these 231 bridges was a cost-effective investment in seismic risk reduction.
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Table 7-9. Benefit-Cost Ratios for Evaluation of Economic Viability of Program to Retrofit 231 Bridges in LA-Testbed System between 1994 and 2004

Exposure Time	50 Years			75 Years			100 Years		
Discount Rate	2.5%	4%	7%	2.5%	4%	7%	2.5%	4%	7%
Benefit-Cost Ratio	3.90	3.19	2.41	4.45	3.42	2.45	4.74	3.51	2.46

7.5.4.2 Standard Deviation of Losses

Table 7-10 compares the standard deviations of the estimated losses for the LA testbed systems with and without the 231 bridge retrofits that occurred between 1994 and 2004.

Table 7-10. Standard Deviations of Losses for use in Evaluation of Economic Viability of Program to Retrofit 231 Bridges in LA-Testbed System between 1994 and 2004

LA-Testbed System	Standard Deviation of Losses	Ratio of Standard Deviation of 2004 System to that of 1994 System
As of Early 1994 (prior to additional 231 bridge retrofits)	$218,634,766	0.616
As of End if 2004 (after completing additional 231 bridge retrofits)	134,718,179	

This table shows that the standard deviation of the losses is reduced by over 38 percent when the additional 231 bridge retrofits are in place. Therefore, when the seismic retrofits of the additional 231 bridges are in place, the volatility (i.e., riskiness) of Caltrans' seismic-retrofit investment is substantially reduced.

7.6 CLOSING COMMENTS

This demonstration application of REDARS™ 2 to SRA of a large highway system in the greater LA area has demonstrated: (a) the range of results that can be obtained from deterministic or probabilistic application of the software; (b) how such results may be interpreted to facilitate pre-earthquake planning and post-earthquake emergency response; (c) how REDARS™ 2 results can facilitate evaluations of the economic feasibility of various seismic improvement options; and (d) how computed confidence-intervals for probabilistic SRA results may be used to assess whether a sufficient number of simulations has been developed. These and other aspects of the use of REDARS™ 2 are further discussed in Chapters 2 and 9.

CHAPTER 8: CONCLUSIONS

8.1 SUMMARY

This Technical Manual describes results from six-years of work to: (a) upgrade the SRA methodology that had previously been developed under the first FHWA-MCEER highway research project; (b) program this methodology into a public-domain software package named REDARS™ 2; and (c) test and document this software.

The eight earlier chapters and 11 appendices that comprise this Manual describe how these objectives were met. In addition to describing the many upgrades of the SRA methodology, that were completed, these chapters and appendices describe how REDARS™ 2 software can be used to enable a transportation agency to consider relative effects on post-earthquake traffic flows when evaluating various seismic improvement options under consideration. This, in turn, will enable the agency to make a more informed selection of a preferred seismic improvement option. Chapter 7 of this Manual illustrates this through a demonstration application of REDARS™ 2 to a major segment of the Los Angeles CA highway system.

The overall SRA methodology from the first FHWA-MCEER project was the starting point for ;the development of REDARS™ 2. That methodology had the following benefits: (a) it is structured to be modular, thereby facilitating the inclusion of improved models and procedures as they are developed from future research; (b) it is a multidisciplinary tool that is based on a synthesis of models developed by earth scientists, earthquake engineers, transportation system analysts, and risk analysts; and (c) it was designed to provide a variety to deterministic and probabilistic SRA results to meet the varied needs of potential users nationwide. The various upgrades of this SRA methodology that have subsequently been programmed into REDARS™ 2 are summarized below: (see Chap. 2):

- ***Probabilistic Framework.*** The framework for carrying out probabilistic SRA has been significantly extended through development of a variance-reduction procedure. This procedure uses advanced statistical analysis techniques to substantially reduce the number of simulations needed to achieve acceptable confidence intervals for probabilistic estimates of average annual losses from earthquake damage to a roadway system (see App. A and J).

- ***Seismic Hazard Module.*** New enhancements of this module for estimating system-wide site-specific ground-shaking and ground-displacement hazards have included: (a) the development of new earthquake walkthrough tables for Coastal California and the Central United States (see Chap. 3 and App. B); (b) the ability to calculate a wide range of different source-site distance measures, that will facilitate REDARS™ inclusion of a larger library of ground-motion models that may use different distance definitions (see Chap. 3 and App. D); (c) the inclusion of well-recognized models for estimating ground shaking from earthquakes in Coastal California and the Central United States (see Chap. 3 and App. D); and (d) the programming of established models for estimating hazards from liquefaction and surface fault rupture (see Chap. 3 and App. E and F).

- ***Component Module.*** New improvements to this module include: (a) modification of the HAZUS99-SR2 model that is the REDARS™ 2 default model for estimating bridge damage from ground shaking, by calibrating the model against bridge damage observations from the Northridge Earthquake (see Chap.4 and App. G and K); and (b) development of new default models for estimating earthquake damage and repair requirements for approach fills and roadway pavements (see Chap. 4 and App. H).

- ***Network Module.*** The REDARS™ 2 network analysis procedure has been improved to include: (a) a capability for assessing how trip demands as well as travel times are affected by earthquake-induced increases in traffic congestion (b) adaptation of a Duel-Simplex searching algorithm that substantially reduces network analysis run times; and (c) development of an ability to account for different types of trips (i.e., auto vs. various types of freight trips) by including separate O-D trip tables and unit economic-loss parameters for each trip type (see Chap. 5 and App. I).

- ***Economic Losses.*** The REDARS™ 2 economic loss estimation procedure has been extended to include: (a) component repair costs (see. Chap. 5 and 6 and App. G and H); and (b) increased travel times and reduced trip demands caused by increases in traffic congestion due to earthquake damage to the roadway system (see Chap. 5 and 6 and App. I).

- ***Input Data.*** Experience has shown that the effort needed to develop input data for SRA of an actual highway system can be formidable and time-consuming. Therefore, significant effort under this project was directed toward developing user interfaces with REDARS™ 2 that facilitate: (a) location of publicly available databases within the Wizard; (b) definition of study-region boundaries; (c) establishment of the various network, soil, and bridge input databases within REDARS™ 2; (d) definition of boundary conditions in the form of external trip demands from outside of the study-region's highway-roadway network; and (d) checking of network-model connectivity and continuity of O-D zones (see App. C and the companion Import Wizard technical report and user manual by Cho et al. (2006)).

- ***Software Development.*** All of the above features have been programmed into a REDARS™ 2 software package for application on personal computers. This Windows-based software includes an internal GIS capability and an extensive graphical user interface (Geodesy 2004).

8.2 COMMENTS

The following paragraphs provide comments regarding current accomplishments and future directions for further development of the REDARS™ 2 methodology and software:

- REDARS™ 2 is a technically-advanced and user-friendly software package that focuses on SRA of highway systems nationwide. This basic REDARS™ 2 framework can be extended to also address other non-earthquake natural hazards and man-made hazards.

- REDARS™ 2 is intended to provide an improved basis for guiding user assessment of various pre-earthquake seismic-improvement options and post-earthquake emergency-response options that may be under consideration. For pre-earthquake applications, the software can be used with various acceptable-risk procedures to guide the selection of a seismic-improvement option that best meets transportation-agency and community needs (see Chap. 2). As a post-earthquake tool, REDARS™ 2 can be used in real time to estimate potential locations of earthquake-induced traffic bottlenecks and to assess various options for addressing these bottlenecks.

- Much has been accomplished over the years in bringing the REDARS™ 2 SRA methodology and software to its current level of development. However, the further development of additional software improvements and upgraded engineering and scientific models for future inclusion into this software must be an ongoing process. Vital to this development will be the application of this software by transportation agencies and consultants nationwide, and the suggestions and feedback that these users would provide.

- The REDARS™ 2 software has been extensively alpha tested by the REDARS™ development team and has also undergone external beta testing. However, continued application of REDARS™ 2 by future users nationwide will undoubtedly uncover bugs to be corrected as well as areas where the REDARS™ technology and software can be further improved. The REDARS™ development team looks forward to working with future users in addressing these issues as they arise.

8.3 FUTURE DIRECTIONS

In the course of this work, specific recommendations for further development of the REDARS™ 2 SRA methodology and software have been identified. These recommendations are summarized below:

- ***Maintenance and Support.*** There is a need to establish a process for continued maintenance and support of the REDARS™ software. This will be essential for enabling the REDARS™ development team to address bugs that may be uncovered, to address user questions and concerns that may arise, and to keep the software current with operating-system changes that will inevitably occur.

- ***Additional Testing and Application of REDARS 2 Nationwide.*** Thus far, there has been one beta tester of REDARS™ 2 -- the California Department of Transportation (Caltrans) in Sacramento CA. The feedback and beta-testing results received from Caltrans during this process have been immensely helpful to the development and final release of the REDARS™ 2 software. However, additional beta testing and applications of REDARS™ 2 by other transportation agencies and potential users nationwide will be necessary to identify other software issues that may arise, and to be sure that the varied needs of a multitude of future users of the REDARS™ software are being met.

- ***Improved Bridge Fragility Models; Ground Shaking Hazards.*** Work under this project and discussions during past Tri-Center workshops have demonstrated the need to develop improved fragility models for estimating bridge damage due to ground-shaking hazards (TCW 2003 and 2005),. This work should also consider the bridge-attribute data that would be needed as input to the improved models that are developed, and how current publicly-available bridge databases can be extended to include these new data. This will be needed to facilitate the use of these models in future REDARS™ applications to highway systems with many bridges.

- ***Improved Bridge Fragility Models; Ground Displacement Hazards.*** There is also a need to develop improved models for bridges subjected to ground displacement hazards due to liquefaction, landslide, and surface fault rupture. As noted above, input-data needs of the improved models that are developed should also be considered as part of this task.

- ***Improved Seismic Hazard Models.*** The current REDARS™ 2 seismic-hazard module should be extended to include: (a) a landslide-hazards model; (b) upgrade of the current fault-rupture-hazard model to consider multiple fault-rupture segments instead of only a single segment; and (c) augmentation of the current REDARS™ 2 library of ground-motion models with additional established models for estimating ground-shaking hazards nationwide.

- ***Development of Additional Earthquake Walkthrough Tables.*** Thus far, earthquake walkthrough models for Coastal California and the Central United States region have been developed for use in future probabilistic SRA applications of REDARS™ 2 in these regions. Additional walkthrough tables should be developed for use in REDARS™ 2 SRA applications to highway systems in other regions of the country where seismic risks to these systems may be important (e.g., the Pacific Northwest, Utah, South Carolina, New York City and regions of New England nearby and north of Boston).

- ***Network Analysis.*** Further enhancements of the REDARS™ 2 network analysis procedure should include: (a) development of a stochastic route-choice model that accounts for uncertainties in the user's choice of a route within a congested highway system; and (b) development of improved trip-demand calibration tools for use in baseline (pre-earthquake) analyses of system-wide traffic flows and travel times.

- ***Future Software Development.*** To supplement current REDARS™ 2 software-usability features, various upgrades of the software have been recommended by REDARS™ 2 beta testers. These very helpful recommendations have been prioritized for implementation under future REDARS™ 2 software-enhancement activities. A prioritized list of these recommendations can be provided upon request.

- ***Input Data.*** To enhance the development of input data for REDARS™, the formation of a single master database for highway systems nationwide that includes relevant data from the NHPN, HPMS, and NBI databases should be considered.

CHAPTER 9: REFERENCES

Abrahamson, N.A. and Silva, W.L. (1997). "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes," *Seismological Research Letters*, Vol. 68, No. 1, January/February, pp 94-127.

Ang, A.H.-S. and Tang, W.H. (1975). *Probability Concepts in Engineering Planning and Design, Volume I, Basic Principles*, New York: John Wiley & Sons.

Atkinson, G.M. and Boore, D.M. (1995). "New Ground Motion Relations for Eastern North America" *Bulletin of Seismological Society of America*, Vol. 85, No. 1, January, pp 17-30.

Bailey, M. (2005). Personal Communication with Stuart D. Werner.

Baker, J.W. and Cornell, C.A. (2006). "Which Spectral Acceleration Are You Using?," *Earthquake Spectra*, Vol. 22, No. 2, May, pp 293-312.

Bardet, J-P. Tobita, T. Mace, N., and Hu, J. (2002). "Regional Modeling of Liquefaction-Induced Ground Deformation," *Earthquake Spectra*, Vol. 18, No.1, February, pp 19-46.

Bartlett, S.F. and Youd, T.L. (1992). *Empirical Analysis of Horizontal Ground Displacement Generated by Liquefaction-Induced Lateral Spreads*, Report NCEER-92-0021, Buffalo NY: National Center for Earthquake Engineering Research.

Basoz, N. and Kiremidjian, A.S. (1996). *Risk Assessment for Highway Systems*, Technical Report 118, John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Palo Alto CA: Stanford University.

Basőz, N. and Kiremidjian, A. S. (1998), *Evaluation of Bridge Damage Data from the Loma Prieta and Northridge, California Earthquakes*, Technical Report MCEER-98-0004, Buffalo NY: Multidisciplinary Center for Earthquake Engineering Research.

Basőz, N. and Mander, J.B. (1999). *Enhancement of the Highway Transportation Module in HAZUS*, Final Pre-Publication Draft (#7), Washington D.C.: National Institute of Building Sciences, March 31.

Beckmann, M.J., McGuire, C.B., and Winston, C.C. (1956). *Studies in the Economics of Transportation*, Yale University Press, New Haven CT.

Bolt, B. A. (1993). *Earthquakes*, New York: W. H. Freeman and Company.

Buckle, I.G. (2003). "Application of Seismic Risk Analysis Procedures to the Performance-Based Design of Highway Systems," *Advancing Mitigation Technologies and Disaster Response for Lifeline Systems, Proceedings of Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering* (J.E.Beavers, editor), ASCE Technical Council on Lifeline Earthquake Engineering Monograph No. 25, August 10-13, pp 886-895.

California Department of Transportation (Caltrans) (1995). *Northridge Earthquake Recovery, Final Comprehensive Transportation Analysis*, Caltrans District 7, Division of Operations, Los Angeles CA, prepared by Barton-Aschman Associates Inc., Pasadena and Irvine CA, August.

California Geological Survey (CGS) (2005). *Alquist-Priolo Earthquake Fault Zones*., http://www.conserv.ca.gov/CGS/rghm/psha/fault-parameters/htm/faultdata1.htm.

Campbell, K.W. (2003). "Engineering Models of Strong Ground Motions," *Earthquake Engineering Handbook* (edited by W-F Chen and C. Scawthorn), CRC Press, New York NY, pp 5-1 to 5-76.

Center for Earthquake Research and Information (CERI) (2005). *New Madrid Catalog*, http://folkworm.ceri.memmphis.edu/catalogs/html/cat_nm_help.html.

Chiou, B. (2005). Personal Communication with Stuart D. Werner, Craig E. Taylor, and Sungbin Cho.

Cho, S., Gordon, P., Moore, J.E. II, Richardson, H.W., Shinozuka, M., and Chang, S. (2001). "Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Urban Earthquake", *Journal of Regional Science*, Vol. 41, No. 1, pp. 39-65.

Cho, S., Huyck, C.K., Ghosh, S., and Eguchi, R.T. (2006a). *REDARS Validation Report*, Technical Report 06-0007, Buffalo NY: Multidisciplinary Center for Earthquake Engineering Research, August.

Cho, S., Ghosh, S., Huyck, C.J., and Werner, S.D. (2006b). *User Manual and Technical Documentation for the REDARS™ Import Wizard*, Technical Report 06-0015, Buffalo, NY Multidisciplinary Center for Earthquake Engineering Research, November.

Davison, A.C. and Hinkley, D. V (1998). *Bootstrap Methods and their Application*, Cambridge, U.K.: Cambridge University Press.

Daykin, C. D., T. Pentikainen, and M. Pesonen (1994). *Practical Risk Theory for Actuaries*, London: Chapman & Hall.

Dial, R., Glover, F., Karney, D., and Klingman, D. (1979). "A Computational Analysis of Alternative Algorithm and Labeling Techniques for Finding Shortest Path Tree", *Networks*, No. 9, pp 215-248.

Dutta, A. and Mander, J.B. (1998). "Seismic Fragility Analysis of Highway Bridges," *Earthquake Engineering Frontiers in Transportation Systems, Proceedings of the Center-to-Center Project Workshop* (H. Kameda and I. Friedland, editors), INCEDE Report 1999-05, Tokyo Japan, pp 1-36.

Efron, B. and Tibshirani, R.J. (1993). *Introduction to the Bootstrap*, New York: Chapman-Hall.

Evans, S.P. (1976). "Derivation and Analysis of Some Models for Combining Trip Distributions and Assignment," *Transportation Research*, Vol. 10, No.1, pp 37-57.

Federal Emergency Management Agency (FEMA) (2002). *HAZUS®99 Service Release 2 (SR2) Technical Manual*, developed by FEMA through agreements with National Institute for Building Sciences, Washington D.C.

Federal Highway Administration (FHWA) (2003). *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges,* Available via compact disk from FHWA Office of Engineering, Bridge Division, Bridge Management Branch, Washington D.C..

Ferritto, J., Priestley, M.J.N., Werner, S.S., and Taylor, C.E. (1999). *Seismic Criteria for Marine Oil Terminals*, Vol. I, Technical Report TR-2103-SHR, Naval Facilities Engineering Center, Port Hueneme CA, July.

Florian, M. and Nguyen, S. (1976). "On Application and Validation of Equilibrium Trip Assignment Method," *Transportation Science*, Vol. 10, No. 4, pp 374-390.

Florian, M., Nguyen, S. and Pallottino, S. (1981) "A Dual Simplex Algorithm for Finding all Shortest Paths," *Networks*, Vol. 11, pp 367-378.

Frank, M. and Wolfe, P. (1956). "An Algorithm for Quadratic Programming," *Naval Research Logistics Quarterly,* Vol. 3, pp 95-110.

Frankel, A. D, Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., and Hopper, M. (1996). *National Seismic-Hazard Maps, June 1996 Documentation.* Denver, CO: U. S. Department of the Interior, U. S. Geological Survey, Open-File Report 96-532.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rekstales, K.S. (2002). *Documentation for the 2002 Update of the National Seismic Hazard Maps*, Denver, CO: U. S. Department of the Interior, U. S. Geological Survey, Open-File Report 02-420.

Geodesy (2004). *REDARS™ 2 Software Specification Development Plan*, San Francisco CA, September 13.

Hanks, T.C. and Kanamori, H (1979). "A Moment Magnitude Scale," *Journal of Geophysical Research*, Vol. 84, pp 2348-2350.

Hastings, N. A. J. and Peacock, J.B. (1974). *Statistical Distributions*, London: Butterworth & Co (Publishers) Ltd.

Housner, G.W. and Jennings, P.C. (1982). *Earthquake Design Criteria*, Earthquake Engineering Research Institute, Berkeley CA, September.

Jernigan, J.B. (1998). *Evaluation of Seismic Damage to Bridges and Highway Systems in Shelby County, Tennessee*, Ph.D. Dissertation, University of Memphis, Memphis TN, December.

Kramer, S.L. (1996). *Geotechnical Earthquake Engineering*, Prentice-Hall, Inc., 653 pp.

Law, A.M. and Kelton, W.D. (1991). *Simulation Modeling and Analysis*, New York: McGraw-Hill, Inc.

Lemaire, J., Taylor, C.E., and Tillman, C. (1993). "Models for Earthquake Insurance and Reinsurance Evaluations," in *Proceedings of the Second International Symposium on Uncertainty Modeling and Analysis*, Los Alamitos, CA: IEEE Computer Society Press, April.

Mai, P. M. and Beroza, G.C. (2000). "Source Scaling Properties from Finite-Fault-Rupture Models," *Bulletin of the Seismological Society of America*, Vol. 90, No. 3, June, pp. 604-615.

Mander, J.B. (1999). Personal Communication to Stuart D. Werner.

Mander, J.B. and Basoz, N. (1999). "Seismic Fragility Curves for Highway Bridges" *Optimizing Post-Earthquake Lifeline System Reliability, Proceedings of the 5th U.S. National Conference on Lifeline Earthquake Engineering* (W.M. Elliott and P. McDonough, editors), Technical Council on Lifeline Earthquake Engineering Monograph No. 16, August, pp 31-40.

Meyer, Paul L., 1970, *Introductory Probability and Statistical Applications*, Reading, MA: Addison-Wesley Publishing Company.

Moore, E. (1957). "The Shortest Path through a Maze," *Proceedings of International Symposium on the Theory of Switching*. Harvard University Press, Cambridge, Mass, pp. 285-292.

Northern California Earthquake Data center (NCEDC) (2005). *Northern California Earthquake Catalogue Search*, http://quake.geo.berkeley.edu.

Panjer, Harry H. And Gordon E. Willmot, 1992, *Insurance Risk Models*, Schaumburg, Il: Society of Actuaries.

Pape, U. (1974) "Implementation and Efficiency of Moore-Algorithms for the Shortest Route Problem," *Mathematical Programming* 7 (2), pp. 212-222.

Priestley, M.J.N., Seible, F., and Calvi, G.M. (1996). *Seismic Design and Retrofit of Bridges*, John Wiley & Sons, New York NY, 686 pp.

Sadigh, K., Chang, C.Y., Egan, J.A., Makdisi, F., and Youngs, R.R. (1997). "Attenuation Relations for Shallow Crustal Earthquakes based on California Strong Motion Data," *Seismological Research Letters*, Vol. 68, No. 1, January/February, pp 180-189.

Seed, H. B. and Idriss, I. M. (1982). *Ground Motions and Soil Liquefaction during Earthquakes*, Earthquake Engineering Research Institute, Berkeley CA.

Sheffi, Y. (1985), *Urban Transportation Networks*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, pp. 125-129.

Shinozuka, M., Moore, J.E. II, Gordon, P., Richardson, H.W., Chang, S., and Cho, S.B. (1999). "An Integrated Model of Highway Networks and the Spatial Metropolitan Economy," *Earthquake Engineering Frontiers in Transportation Systems, Proceedings of the Center-to-Center Project Workshop* (H. Kameda and I. Friedland, editors), INCEDE Report 1999-05, Tokyo Japan, pp 1-36.

Shinozuka, M. (2004). *Report on Socio-Economic Effect of Seismic Retrofit Implemented on Bridges in Los Angeles Highway Network*, Report prepared for California Department of Transportation, Office of Earthquake Engineering and Structural Design, Irvine CA: University of California, June.

Silva, W., Gregor, N., and Darragh, R. (2002). *Development of Regional Hard-Rock Attenuation Relations for Central and Eastern North America*, Pacific Engineering and Analysis, El Cerritto CA.

Silva, W., Gregor, N., and Darragh, R. (2003). *Development of Regional Hard-Rock Attenuation Relations for Central and Eastern North America, Mid-Continent, and Gulf Coast Areas*, Pacific Engineering and Analysis, El Cerritto CA.

Small, E.P. (1997). "Alternatives for the Integration of Seismic Vulnerability Assessment within the Pontis Bridge Management System," *Proceedings of the National Seismic Conference on Bridges and Highways, Sacramento CA*, Federal Highway Administration and California Department of Transportation, pp 53-64, July 8-11.

Small, E.P. (1999). "Examination of Alternative Strategies for Integration of Seismic Risk in Bridge Management Systems," *Proceedings of the International Bridge Management Conference*, Transportation Research Board, Washington D.C., April,

Southern California Earthquake Center (SCEC) (2005). *Catalog of "A" Quality Earthquake Depths*, derived from http://www.data.scec.org/catalog-search/date-mag_loc.php.

Taylor, C. E., Lemaire, J., and Tillman, C. (1994). "A New Earthquake Insurance and Reinsurance Index: Uncertainties and Future Developments," *Uncertainty Modeling and Analysis: Theory and Applications*, B. M. Ayyub and M. M. Gupta, eds., Elsevier Science BV., pp. 497-514.

Taylor, C.E., Eguchi, R.T., and Chang, S. (1998). “Updating Real-Time Earthquake Loss Estimates: Methods, Problems, and Insights,” *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering, Seattle WA*, Oakland CA: Earthquake Engineering Research Institute, May 31- June 4, 484pdf, CD-ROM,

Taylor, C.E., Werner, S.D., and Jakubowski, S. (2001). “The Walkthrough Method for Catastrophe Decision Making,” *Natural Hazards Review*, Vol. 2, No. 4, American Society of Civil Engineers, November, pp 193-202.

Taylor, C.E., Perkins, D.M., and Werner, S.D. (2004a). *Post-Sampling Variance Reduction for Seismic Risk Analysis of Spatially Distributed Lifeline Networks*, Technical Report for the Multidisciplinary Center for Earthquake Engineering Research under research contract FHWA Contract DTFH61-98-C-00094, July.

Taylor, C.E., Werner, S.D., Silva, W., Aschheim, M., and Scheibel, L. (2004b). *Exogenous Uncertainties in Earthquake Risk Modeling for Infrastructure Systems: A Demonstration Evaluation in Northern California*, Torrance, CA: Natural Hazards Management Inc. for the United States Geological Survey, Award No. 03HIGR0022, August.

Tri-Center Workshops (TCW) (2003 and 2005). Collaborative Workshop of Researchers in Bridge Earthquake Engineering, Seismic Risk Analysis of Highway Systems, and Transportation Network Analysis, Multidisciplinary Center for Earthquake Engineering Research (MCEER), Mid-America Center for Earthquake Engineering Research (MAE), and Pacific Earthquake Engineering Research Center (PEER), June 2003 (San Pedro CA), December 2003 (Las Vegas NV) and October 2005 (Las Vegas NV).

Tokimatsu, K. and Seed, H B, (1987). “Evaluation of Settlements in Sands due to Earthquake Shaking,” *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 113, No. 8, August, pp 861-878.

Toro, G.R. Abrahamson, N.A., and Schneider, J.F. (1997). “Model of Strong Motions from Earthquakes in Central and Eastern North America: Best Estimates and Uncertainties’, *Seismological Research Letters*, Vol. 68, No. 1, January/February, pp 41-57.

Wardrop, J.G. (1952). “Some Theoretical Aspects of Road Traffic Research,” *Proceedings, Institution of Civil Engineers*, Vol. II, No.1, pp 325-378.

Wakabashi, H. (1999). “Highway Network Reliability Assessment and Importance Analysis: Lessons Learned from the 1995 Kobe Earthquake,” *Earthquake Engineering Frontiers in Transportation Systems, Proceedings of the Center-to-Center Project Workshop*, (H. Kameda and I. Friedland, editors), INCEDE Report 1999-05, Tokyo Japan, pp 151-166.

Wells, D.L. and Coppersmith, K.J. (1994). "New Empirical Relationships among Magnitude, Rupture Length, Rupture Area, and Surface Displacement," *Bulletin of Seismological Society of America*, Vol. 84, No. 4. August, pp 974-1002.

Werner, S.D. and Taylor, C.E. (2002). "Component Vulnerability Modeling Issues for Analysis of Seismic Risks to Transportation Lifeline Systems," *Acceptable Risk Processes: Lifelines and Natural Hazards* (edited by Craig Taylor and Erik VanMarcke), Monograph No. 21, Reston VA: American Society of Civil Engineers Council on Disaster Reduction and Technical Council on Lifeline Earthquake Engineering, March, pp 78-104.

Werner, S. D., Dickenson, S.E., and Taylor, C.E. (1997). "Seismic Risk Reduction at Ports: Case Study and Acceptable Risk Evaluation," *Journal of Waterway, Port, and Coastal Engineering, American Society of Civil Engineers*, Vol. 123, November-December, pp 337-346.

Werner, S.D., Taylor, C.E., and Ferritto, J.M. (1999). "Seismic Risk Reduction Planning for Ports Lifelines", Optimizing Post-Earthquake Lifeline System Reliability, *Proceedings of the Fifth U.S. Conference on Lifeline Earthquake Engineering,* Seattle WA, Technical Council on Lifeline Earthquake Engineering Monograph 16 (Edited by W. M. Elliot and P. McDonough), American Society of Civil Engineers, Reston VA, pp 503-512, August.

Werner, S.D., Taylor, C.E., Moore, J.E. III, Walton, J.S., and Cho, S. (2000). *A Risk-Based Methodology for Assessing the Seismic Performance of Highway Systems*, Buffalo, NY: Multidisciplinary Center for Earthquake Engineering Research, Technical Report MCEER-00-0014, FHWA Contract Number DTFH61-92-C-00016., December.

Werner, S.D., Taylor, C.E., Dahlgren, T., Lobedan, F., LaBasco, T.R., and Ogunfunmi, K. (2002). "Seismic Risk Analysis of Port of Oakland Container Berths," *Proceedings of Seventh U.S. Conference on Earthquake Engineering*, Boston MA, July 21-25, CD-ROM.

Werner, S.D., Lavoie, J-P, Eitzel, C., Cho, S., Huyck, C., Ghosh, S., Eguchi, R.T., Taylor, C.E., and Moore, J.E. II (2003). "REDARS™ 1 Demonstration Software for Seismic Risk Analysis of Highway Systems," *Research Progress and Accomplishments 2001-2003*, Report MCEER-03-SP01, Buffalo NY: Multidisciplinary Center for Earthquake Engineering Research, May, pp 17-34.

Werner, S.D., Taylor, C.E., Cho, S., Lavoie, J-P, Huyck, C.K., Eitzel, C., Eguchi, R.T., and Moore III, J.E. (2004). "New Developments in Seismic Risk Analysis of Highway Systems," *Proceedings of 13th World Conference on Lifeline Earthquake Engineering, Vancouver B.C., Canada*, Paper No. 2189, August 1-6.

Yashinsky, M. (2005). Personal Communication with Stuart D. Werner.

Youd, T. L. (1998). *Screening Guide for Rapid Assessment of Liquefaction Hazard at Highway Bridge Sites*, Provo, Utah: Brigham Young University for National Center for Earthquake Engineering Research, Buffalo NY under NCEER Task 106 E-3.1(B), FHWA Contract DTFH61-92-C-00106.

Youd, T.L. (2002). “Pavements,” Chapter 6 of *Seismic Retrofitting Manual for Highway Structures: Retaining Structures, Slopes, Tunnels, Culverts, and Pavements*, Buffalo NY: Multidisciplinary Center for Earthquake Engineering Research, January.

Youd, T. L. and Perkins, D. L. (1978). “Mapping of Liquefaction Induced Ground Failure Potential,” *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 104, No. GT4, April, pp 433-446.

Youngs, R.R., Abrahamson, N.A., Makdisi, F., and Sadigh, K. (1995). “Magnitude-Dependent Dispersions in Peak Ground Acceleration’, *Bulletin of the Seismological Society of America*, Vol. 85, pp 1161-1176.

Youngs, R.R., Arabascz, W.J., Anderson, R.E., Ramelli, A.R., Ake, J.P., Slemmons, D.J., McCalprin, J.P., Doser, D.I., Fridrich, C.J., Swan III, F.H., Rogers, A.M., Yount, J.C., Anderson, L.W., Smith, K.D., Brahn, R.L., Knuepfer, P.L.K., Smith, R.B., dePolo, C.M., O’Leary, D.W., Coppersmith, K.J., Pezzopane, S.K., Schwartz, D.P., Whitney, J.M., Olig, S.S., and Toro, G.R. (2003).“A Methodology for Probabilistic Fault Displacement Hazard Analysis (PFDHA),” *Earthquake Spectra*, Vol. 19, No. 1, February, pp 191-219.

Note

Appendices A through K in "REDARS 2 Methodology and Software for Seismic Risk Analysis of Highway Systems" are included in PDF format on the CD in the back of this book. The titles are as follows:

Appendix A. Probabilistic Framework
Appendix B. Earthquake Scenarios and Walkthrough Files
Appendix C. Import Wizard
Appendix D. Source-Site Distances and Ground Motion Hazards
Appendix E. Liquefaction Hazards
Appendix F. Surface Fault Rupture Hazards
Appendix G. Default Bridge Modeling Procedures
Appendix H. Default Models for Approach Fills and Roadway Pavements
Appendix I. Post-Earthquake Trip Reduction and Updated Minimum Path Algorithm in Network Analysis Procedure
Appendix J. Confidence Limits for Probabilistic Seismic risk Analysis Results
Appendix K. Calibration of Default Bridge Damage Model

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