STATE OF CALIFORNIA DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV. 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA06-0266		

4. TITLE AND SUBTITLE	5. REPORT DATE / 6. PERFORMING ORGANIZATION CODE
REDARS™ 2 DEMONSTRATION PROJECT FOR SEISMIC RISK ANALYSIS OF HIGHWAY SYSTEMS	5. REPORT DATE: June 2006 6. PERFORMING ORGANIZATION CODE:
7. AUTHOR(S) Stuart D. Werner, Sungbin Cho, Craig E. Taylor, Jean-Paul Lavoie, Charles Huyck, and Ronald T. Eguchi	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS California Department of Transportation Division of Research and Innovation, MS-83 1227 O Street Sacramento CA 95814	10. WORK UNIT NUMBER 11. CONTRACT OR GRANT NUMBER: 65A0149
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Sacramento, CA 95819	13. TYPE OF REPORT AND PERIOD COVERED: Final Report, June 2006 14. SPONSORING AGENCY CODE

15. SUPPLEMENTAL NOTES

16. ABSTRACT

Effects of earthquake damage to highway components such as bridges and roadways can go well beyond life-safety risks and costs to repair damaged structures. Such damage can also severely disrupt traffic flows that can impact the region's economy and its post-earthquake emergency response and recovery. These impacts will depend not only on the seismic performance of the components, but also on the characteristics of the overall highway system such as its network configuration and its trip demands. Unfortunately, such traffic impacts are usually not considered in seismic improvement activities at transportation agencies. One reason has been the lack of a technically sound and practical methodology for estimating these impacts. The Federal Highway Administration (FHWA) has funded research through the Multidisciplinary Center for Earthquake Engineering Research (MCEER) to develop methods to reduce the seismic vulnerability of roadway systems and components over the past 12 years. One of the tasks in this research program has focused on the development, programming, and application of a new state-of-the-art methodology for deterministic and probabilistic seismic risk analysis (SRA) of roadway systems nationwide. This work has culminated in the recent release of a software package named REDARS™ 2 for assessing the time-dependent impacts of earthquakes on a transportation network in terms of traffic delays and economic losses. In addition, over the past three years, the California Department of Transportation (Caltrans) has carried out a REDARS™ Demonstration Project. This project, which is described in this report, was aimed at transferring technical expertise from the developer community at FHWA and MCEER to Caltrans. In particular, the project was to enable Caltrans' staff to assess the applicability of the REDARS™ for: (a) pre-earthquake planning of seismic-risk-reduction measures; and (b) post-earthquake emergency response in real time after an actual earthquake. The project has also supported the improvement of several models within REDARS™ -- which is an effort that was facilitated by close interaction between the REDARS™ Development Team (RDT) and Caltrans staff. Finally, Caltrans' staff has beta tested the REDARS™ 2 software, and has provided the RDT with helpful suggestions for future methodology and software upgrades.

17. KEY WORDS	18. DISTRIBUTION STATEMENT	
Seismic risk assessments (SRA). Highway infrastructure. Highway systems. Risk of Earthquake Damage for Roadway Systems (REDARS) software program. Post-earthquake analyses. Ground motion. Bridge fragility models. Traffic state models. Transportation network models. Economic loss models. Uncertainty.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. SECURITY CLASSIFICATION (of this report)	20. NUMBER OF PAGES	21. PRICE
Unclassified	237	

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Final Report

REDARS™ 2 DEMONSTRATION PROJECT FOR SEISMIC RISK ANALYSIS OF HIGHWAY SYSTEMS

by

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Prepared under Research Project entitled

Caltrans REDARS™ Demonstration Project

(Caltrans Agreement No. 65A0149)

for

California Department of Transportation
Sacramento, California

June 2006

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DISCLAIMER STATEMENT

ACKNOWLEDGEMENTS

This final report is based on research and programming performed under California Department of Transportation (Caltrans) Agreement 65A0149 with Seismic Systems & Engineering Consultants, Oakland, California. The project on which this report is based is titled *Caltrans REDARS™ Demonstration Project*. The project began on July 1, 2003 and was completed on June 30, 2006.

This SRA research and programming was performed by a REDARS™ Development Team (RDT) with close collaboration with Caltrans technical staff. The RDT was comprised of Stuart D. Werner of Seismic Systems & Engineering Consultants (earthquake engineering, and project manager), Sungbin Cho of ImageCat Inc. (network analysis, data analysis, and seismic analysis support), Jean-Paul Lavoie of Geodesy (lead programmer for the REDARS™ 2 seismic risk analysis software), Charles K. Huyck of ImageCat Inc. (data analysis and technical support), and Ronald T. Eguchi of ImageCat Inc. (internal project review). Other significant contributors to the work performed by the RDT were Chip Eitzel of Geodesy (programming support), James E. Moore II of the University of Southern California (network analysis consultation), and Howard Chung and Shubharoop Ghosh of ImageCat Inc. (data analysis and programming support).

The Caltrans team that closely collaborated with the RDT and provided very helpful support and recommendations throughout this project consisted of Mandy Chu (Caltrans' project manager) and Zhongren Wang, Loren Turner, Brian Chiou, and Mike Jenkinson (Caltrans beta testers and project technical staff). In addition, Cliff Roblee, formerly of Caltrans and now with NEES Consortium Inc., provided valuable technical review during the early stages of the project.

The following additional Caltrans staff contributed substantially to the component modeling and engineering aspects of this project: Tom Harrington and Steve Sahs (bridge repair-modeling);- Dan Adams, Paul Altamura, and Minh Ha (approach fill modeling); Bill Weber, Leo Mahserelli, Kirsten Stahl, Bill Farnbach, and Tinu Mishra (pavement modeling); Randy Anderson and Ray Mailhot (Caldecott Tunnel modeling); Kevin Thompson, Ganapathy Murugesh, and Foued Zayati (user-specified bridge fragility modeling); Mark Yashinsky (bridge earthquake engineering); Tom Shantz (geotechnical earthquake engineering); and Matt Bailey (bridge-retrofit cost estimation).

Some material contained in this report was drawn from research conducted as part of a multi-year seismic research project conducted by the Multidisciplinary Center for Earthquake Engineering (MCEER), Buffalo NY, under the sponsorship of the Federal Highway Administration (FHWA). This research resulted in the development of the basic SRA methodology and software development that has led to the REDARS™ 2 software package. Significant contributors to that work were Phillip Yen of FHWA; Ian Buckle of the University of Nevada at Reno; George Lee of MCEER and the State University of New York at Buffalo; Jerry O'Connor of MCEER; Masanobu Shinozuka of the University of California at Irvine; and the FHWA-MCEER Highway Seismic Research Council and its Research Advisory Committee (which included Charles Kircher, Keith Porter, Edgar Small, and Steve Leung).

CONTENTS

CONTENTS

Chapter/Section | **Page**

CONTENTS

CONTENTS

CONTENTS

CONTENTS

CONTENTS

CONTENTS

APPENDIX A
PROBABILISTIC FRAMEWORK

A.1 OBJECTIVE AND SCOPE

The basic probabilistic framework for the REDARS™ 2 SRA methodology is a walkthrough procedure, which is a Monte Carlo time-series method (buttressed by a new bootstrap post-sampling method). Through use of random methods, this procedure avoids statistical biases present in other procedures in which scenario earthquakes (with specified magnitudes and locations) and simulations (the random estimation of losses due to these specific scenarios) are not picked randomly. At the same time, as a time-series method, the walkthrough method permits the evaluation of decisions in which time-considerations are critical.

This appendix updates previous accounts of the probabilistic framework for the REDARS™ walkthrough procedure, as found in Werner et al. (2006) and Taylor et al. (2001). It is organized into three remaining sections that: (a) provide an overview of the walkthrough procedure (Section A.2); (b) discuss basic concepts behind this procedure (Section A.3); and (c) show how loss distributions are developed from the loss results for each scenario earthquake and simulation (Section A.4).

Two major new developments in this probabilistic framework are covered in other appendices. One new development that is described in Appendix C consists of a more detailed specification of earthquake scenarios, so that various "distance" calculations (for alternative attenuation functions and for various other modules such as those estimating liquefaction displacements) can be accommodated. A second new development that is described in Taylor et al. (2004) and Werner et al. (2006) uses a new bootstrap (sampling with replacement) "variance-reduction" procedure to develop loss estimates and their nominal confidence intervals much more efficiently than the earlier method based on classical statistics that is described in Werner et al. (2000). Improvements in the hazards, component vulnerability, and network analysis models as described in the main chapters of this report also constitute important updates of the REDARS™ probabilistic framework.

A.2 WALKTHROUGH PROCEDURE: OVERVIEW

The walkthrough procedure is carried out for a user-specified duration (in years) that is established in accordance with basic principles summarized below. The procedure randomly selects values of the various uncertain parameters contained in the models that comprise the REDARS™ 2 SRA procedure, and then carries out a SRA using this set of parameters in order to develop one simulation of potential losses due to earthquake damage to the roadway system (Sections A.2.1 and A.2.2.) This process is then repeated in order to develop additional simulations, and probabilistic loss distributions and statistics are developed from the SRA results for each simulation developed so far. These results include the estimation of confidence intervals for the loss results from all of the simulations developed thus far, in order to guide the user's assessment of whether or not a sufficient number of simulations has been considered (Section A.2.4).

A.2.1 Scenario Earthquakes

A set of independent uniform random numbers is generated and used with regional seismicity and tectonics models to establish whether any potentially damaging earthquakes[1] occur in the surrounding region during each year of the walkthrough (i.e., for years 1, 2, etc.) For many simulated years, no damaging earthquakes will be found to occur, particularly for moderately seismic regions. For other years, it will be determined that one or more potentially damaging earthquakes occur. Additional series of uniform random numbers are then used with these models to establish the magnitude, location, rupture center, and rupture length of each of these earthquakes. This is provided in tabular form (for each year of the walkthrough) as a walkthrough table for input into the SRA calculations. Section 4.2 summarizes how this procedure has been used to develop an earthquake walkthrough table that is suitable for use in Caltrans' future application of REDARS™ 2 to highway-roadway systems statewide.

A.2.2 Simulation Development Process

The REDARS™ 2 SRA procedure accounts for uncertainties in: (a) earthquake occurrence, magnitude and location; (b) ground motion attenuation rates and soil amplification effects; (c) liquefaction-induced lateral-spread displacements; (d) surface fault rupture displacements; and (e) bridge, tunnel and approach fill damage states due to ground shaking and permanent ground displacement. These uncertainties are considered by developing multiple "simulations" of earthquake-induced losses for successive years in the walkthrough table, as summarized below:

- ***Step 1. Scenario Earthquakes.*** Randomly sample an appropriate earthquake model for the region, in order to establish, for each year of the walkthrough, whether or not one or more earthquakes occur during that year and, if so, their magnitudes and locations.

- ***Step 2. Seismic Hazards.*** For each scenario earthquake, randomly sample the probability distributions from the ground motion, liquefaction, and fault rupture models to develop a random value of each of these hazards at each component site within the roadway system.

- ***Step 3. Component Performance.*** For the above set of seismic hazards at each site, randomly sample the fragility curves for the various components in the roadway system, in order to estimate each component's damage state. Then, using default or user-specified repair models, estimate each component's corresponding repair costs, repair time, and traffic state (i.e., ability to carry traffic at various post-earthquake times, while the repairs are proceeding). Note that these variations of traffic states with time after the earthquake reflect the repair-model's estimated rate of repair of the damage to the component.

- ***Step 4. System States.*** Using the above traffic states for each component at each post-earthquake time, develop a series of system states -- one for each post-earthquake time. As noted in Section 2.0, each system state is essentially a "snapshot" of the entire roadway system at that post-earthquake time, which shows which roadway links throughout the system are fully closed, partially closed, and fully open to traffic during that time.

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[1] Potentially-damaging earthquakes are defined as those events whose moment magnitude ≥ 5.0.

- ***Step 5. Network Analysis.*** Apply the REDARS™ 2 network analysis procedure to each system state, in order to estimate corresponding system-wide travel time delays, traffic flow disruptions, and reductions in trip demands at that post-earthquake time.

- ***Step 6. Losses.*** Estimate the losses due to earthquake damage to the roadway system. In this, the term "loss" can represent economic loss, increase in travel time to/from any key location in the region, increase in travel times along key "lifeline" routes within the system, reductions in trips to/from any location in the region, or any other adverse consequence of earthquake damage to the roadway system.

The results of the above steps as applied for each scenario earthquake in the walkthrough table is termed a "simulation". However, since "years" are a basic constituent in key loss statistics, one may speak of year-trials or year-samples. Year-trials for which no scenarios are postulated will have no losses. In years for which there is more than one scenario postulated, the losses during that year (for the year-trial) are the combination of losses for each scenario.

After simulations are developed for a sufficient number of years of the walkthrough (see Sec. A.2.3), REDARS™ 2 analyzes the loss results from these simulations developed so far, and develops probabilistic estimates of system-wide losses. REDARS™ 2 uses similar procedures to develop probabilistic estimates of seismic hazards (ground motions and permanent ground displacements) at any user-specified component site in the roadway system, as well as probabilistic estimates of damage states for any user-specified component.

A.2.3 Nominal Confidence Levels and Limits

The steps outlined in Section A.2.2 do not necessarily need to be carried out for all years of the walkthrough table. Rather, REDARS™ 2, uses procedures described in Taylor et al, (2004) and Appendix J of Werner et al. (2006), in order to estimate nominal confidence intervals (CIs) for the loss results from the walkthrough years (and corresponding simulations) considered so far. If the user determines that these nominal CIs are inadequate, additional walkthrough years are considered and new simulations are developed for each of these additional years. Revised loss distributions are then obtained from all of the walkthrough years and simulations considered so far, and new nominal CIs are estimated from this now-expanded number of simulations. This process is repeated until the user determines that the nominal CIs are acceptable. At that time, the walkthrough analysis can be terminated.

A.3 WALKTHROUGH PROCESS: UNDERLYING CONCEPTS

Key to the above walkthrough process are the concepts of random sampling, Bernoulli trials, and the planning horizon (exposure times) that is used to assess the probabilistic loss results. These concepts are summarized below.

A.3.1 Random Sampling

As noted in Section A.2, random sampling is used to establish the value of each uncertain parameter used in the SRA for each simulation that is developed. Modern statistical theory has shown that this use of random sampling methods for a relatively small number of samples will greatly increase statistical soundness (e.g., the lack of statistical bias, the ability to estimate CIs) relative to that for non-random sampling for a much larger number of samples[2]

A.3.2 Bernoulli Trials

The notion of Bernoulli trials fits well with the above random sampling process and the establishment of confidence intervals for the SRA results. A Bernoulli trial is a statistical sampling process in which: (a) each sample is independent of all other samples; and (b) the probability remains constant for each sample. It is assumed here -- with some caveats as discussed below -- that the SRA results developed from the above walkthrough process can be treated as Bernoulli trials. Taylor et al. (2004) describes how this assumption facilitates the development of nominal CIs that, in turn, will guide the user's assessment of whether a sufficient number of walkthrough years and corresponding simulations have been considered.

To illustrate the Bernoulli trial concept, suppose that 10,000 years are simulated as described in Section A.2.1, in order to estimate earthquake losses. Assuming that each year leads to an independent statistical sample, each of these estimated losses will have an equal probability of occurrence (of 1/10,000). The number of non-zero losses from these 10,000 years of simulations will depend on the regional seismicity and tectonics and on the seismic-response characteristics of the roadway-system components. For example, in the Los Angeles area roadway system analyzed in Appendix D, approximately 2,600 of these 10,000 simulated losses are non-zero (even though the earthquake sources for these losses will have widely varying probabilities.)

There are certain caveats in the use of this Bernoulli trial assumption in this methodology for estimating risks and losses due to earthquake damage to a roadway system. Minor caveats pertain to how diverse earthquake faults may be modeled in a non-Poissonian fashion. Selected faults can be modeled as having very slightly varying probabilities from year except after an event on the fault, when probabilities drop precipitously. Major caveats primarily pertain to downstream modeled changes in traffic and traffic patterns, the roadway network itself, and seismic modifications to pertinent components and soils. To anticipate the next section, the basic "independent unit" of time will be a planning horizon whose duration can be the basis for each Bernoulli trial.

A.3.3 Planning Horizon

Used basically to develop statistics such as average annualized losses, the walkthrough process can be conceived of as consisting of a large number of Bernoulli trials (10,000 trials for a 10,000 year walkthrough). Models of earthquake faults in which probabilities change from year to year do not impact this case, because one can merely use the probability for the "next year."

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[2] For example, in the 1936 presidential election, a straw poll of 3,000,000 respondents (without random sampling) predicted that Alf Landon would be a clear winner over Franklin Roosevelt. Modern random sampling methods would require polling of only about of about 1,000 (rather than 3,000,000) respondents, and are deemed to be much more accurate than a straw poll of a biased sample of respondents (Taylor et. al., 1998).

However, the walkthrough method is designed as a time-series method principally because it can also be used to consider modifications over different planning horizons, e.g., with durations of say 5-years, 10-years, 25-years, or 50-years. Significant modifications over time can be expected in traffic patterns and trip demands. Likewise, there may be projected changes in roadway components and links, and in their seismic resistance (through seismic upgrade, etc.).

REDARS™ 2 cannot now consider effects of such projected changes over time. However, to the extent that reliable projections can be made over various planning horizons, REDARS™ 2 can be readily extended to evaluate effects of projected changes and various alternative changes as well. For instance, one may project changes in traffic demands from year to year and projected new links in some specific years. If, for example, a five-year planning horizon is used for a 10,000-year walkthrough, then 2,000 simulations or Bernoulli trials of this five-year planning horizon can be developed.

Within this notion of a planning horizon, a non-Poissonian evaluation of the rate of occurrence on a specific fault system can be readily accommodated. Probabilities can be developed, say, for each of the next five years and, if an event is randomly picked on this fault system for any of the first four years, then the probabilities of occurrence of an event on this fault for subsequent years can be suitably reduced.

Very long planning horizons such as 50-years and 100-years are less suitable for the time-series evaluation of travel-time losses in REDARS™ 2. In particular, projections can be very unreliable for such long planning horizons. In these cases, one may use REDARS™ 2 merely to develop pertinent statistics as described in the opening paragraph of this section. These longer-term exposures are more suitably applied to the evaluation of downtimes and probabilities of various levels of damage for individual components within a transportation system because such components often have long exposure periods.

A.4 DEVELOPMENT OF LOSS DISTRIBUTIONS

Once the probabilistic SRA results are obtained from the walkthrough analysis framework summarized in Section A.2, they can be used to develop either total loss distributions or conditional loss distributions, as described below.

A.4.1 <u>Total Loss Distribution</u>

A total loss distribution is a plot of loss value vs. the probability that this value will be exceeded during a designated exposure time. The process for establishing a total loss distribution from the SRA walkthrough results is summarized below, for the general case of Y' simulations (i.e., Y' Bernoulli Trials) for estimation of losses.

- The results of the walkthrough analysis are given as an output matrix with Y' rows and two columns. In each row, the first column contains the trial number, and the second column contains the value of the total loss for that trial. In this matrix, most of the Y' rows will have no potentially damaging earthquake occurrence.

- Each of these Y' loss-severity estimates is treated as a statistical sample of the loss due to earthquake damage to the roadway system. Each sample is assumed to be equally probable, with a frequency of occurrence of. $1/Y'$.

- The Y' loss values are arranged in decreasing order with the highest value first, the next highest value second, and so on. Then, the i^{th} loss value, L_i, in this sequence is considered to have a frequency of exceedance of X_i, which is the number of occurrences of loss values equal to or greater than L_i. For example, the frequency of exceedance of the first (highest) loss value is $1/Y'$, and the frequencies of exceedance of subsequent loss values in the sequence are $2/Y'$, $3/Y'$, and so on.

- For an exposure time of T years, the probability P_i that the loss L will equal or exceed the i^{th} loss value, L_i, is computed from the following Poisson equation:

$$P_i = P(L \geq L_i) = 1 - \exp(-TX_i) \tag{A-1}$$

- The results of the walkthrough analysis are given as an output matrix with Y' rows and two columns. In each row, the first column contains the trial number, and the second column contains the value of the total loss for that trial.

A.4.2 Conditional Loss Distribution

A similar procedure to that outlined above for development of total loss distributions can be used to develop conditional loss distributions. For example, suppose that it is desired to develop loss distributions that are conditional on the occurrence of a particular earthquake event with a designated magnitude and location. Also suppose that S simulations (that account for uncertainties in estimation of seismic hazards and component damage states) are to be used to develop this conditional loss distribution. Then, the user carries out the SRA and loss estimation for these S simulations and the fixed earthquake event. Finally, for this set of results, the user repeats the above procedure for development of a total loss distribution. This involves: (a) forming a loss matrix with S rows and two columns; (b) assuming all of the loss values have an equal probability of $1/S$; (c) ordering the loss results for each simulation in decreasing order; and (d) adapting Equation A-1 to estimate the probability of exceedance for each loss value.

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APPENDIX B
IMPORT WIZARD

B.1 BACKGROUND

REDARS™ 2 requires the integration of several data sets from various federal, state, and local government agencies that characterize the highway system, its seismic hazards, bridges and other components. Previously, users of this software had to manipulate the raw data into a transportation network format that is suitable for a REDARS™ 2 traffic-flow analysis. However, this is a significant and time-consuming effort. Therefore, the Import Wizard was developed to automate most of this data manipulation, and to thereby significantly reduce input preparation time and to also reduce the potential for incorrect input data in REDARS™ 2.

This appendix summarizes the Import Wizard and how it imports data into REDARS™ 2. In this, an effort has been made to include as much publicly available and federally distributed data as possible. This minimizes the user's tasks associated with collecting the data. The Import Wizard also guides the user through the process of identifying databases on the hard drive, and integrates the various default or user-specified data sets into the required REDARS™ 2 format. An additional more detailed description of the Import Wizard is provided in Cho et al., (2006a).

B.2 ROLE OF IMPORT WIZARD AND ITS GRAPHICAL USER INTERFACE

The role of the Import Wizard is to assign the paths to the input-data files and to define the study region (see Figure B-1). The input data files are either default national databases or databases that the user specifies in a predefined format. The Import Wizard locates these files and defines the study area, based on the extent of the analysis that the user specifies. Its final product is a database that defines the study area's highway system, bridges, soils, and origin-destination trip tables, and can be directly input into the REDARS™ 2 core program.

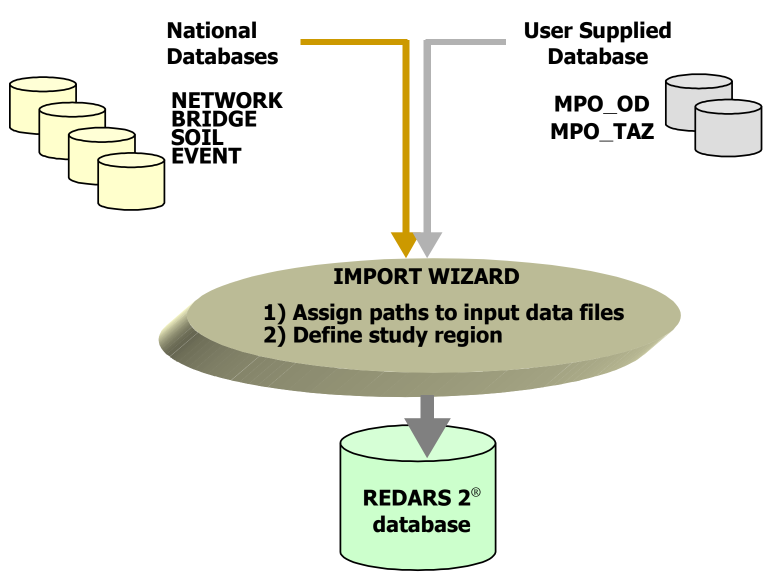


Figure B-1. Role of the Import Wizard

The Graphical User Interface (GUI) for the Import Wizard guides the user through a series of simple steps for identifying the data sources needed to create the REDARS™ 2 input database. It provides brief explanations of the steps involved, the data sources, default and optional data the user might want to use, and the format of data to be used. When geographic data sources are to be identified, the GUI describes the required file formats, coordinate system, datum etc for geographic file, and also provides file formats required for other file types. In addition, the GUI provides simple geographic information system (GIS) tools that enable the REDARS™ 2 user to select a study region for analysis by a series of simple clicks on a map.

B.3 LIMITATIONS OF IMPORT WIZARD

The REDARS™ 2 Import Wizard uses nationally available FHWA datasets to enable prompt creation of highway-roadway network study regions. Although the program depends on FHWA data, the actual datasets are provided by the states themselves. They may vary in accuracy and completeness, depending on the original developer's interpretation of data requirements and the completeness of the base data. These factors, in turn, will affect the usability of the databases for a given area. The following paragraphs identify such difficulties that may arise due to problems with a region's base data and, where possible, recommends solutions to these difficulties.

- In the roadway network study region, bridges may be missing or misplaced. This is often due to problems in the Linear Referencing System (LRS) of the base data. For example, some state transportation agencies do not track subroute ID, or do so in a manor that is inconsistent with National Bridge Inventory (NBI) data. Milepost markers are often incorrect, reversed, or in the wrong units, which results in misplaced or omitted bridges. Possible solutions include correcting the LRS in a GIS system, or editing the original-data fields to be consistent with the NBI data.
- The NBI, the National Highway Planning Network (NHPN) and the Highway Performance Monitoring System (HPMS) do not contain sufficient information for locating bridges on ramps. A freeform field in the NBI data does accommodate entering the information, but this is rarely entered consistently enough to parse bridge location. At this time, REDARS™ 2 conservatively assumes that damaged ramps impact traffic in both directions of the freeway.
- The attribute data may contain incorrect or no information regarding number of lanes, link type, rural or urban designation, and route attributes. Such base-data issues must be resolved by the REDARS™ 2 user, after which the Import Wizard can be rerun..
- The NBI only tracks state and federal bridges which are located primarily on freeways and highways. If desired by the REDARS™ 2 user, more detailed network data can be obtained from the cognizant Metropolitan Planning Organization (MPO) for the region, and more detailed bridge data can be obtained from local jurisdictions. These data will vary by region and are not supported by the Import Wizard. Users can create a roadway network study region outside of the Import Wizard using the REDARS™ 2 open database format.
- Public transit is currently not supported within REDARS™ 2. One-way routes are not distinguished in the NHPN data. Users can represent one-way routes by deleting the extra directional link record in the final REDARS™ 2 input data for the study region.

B.4 DATA SOURCES

In order to model the effects of a seismic event on the transportation network, the Import Wizard integrates different types of nationally available geospatial databases and creates a REDARS™ 2 study region through database queries and software code. Underlying the REDARS™ 2 study region is a database containing link, node, bridge, and OD tables for transportation analysis. The sources of data that populate these underlying tables include NHPN and HPMS databases for the transportation network, the NBI database for bridges, National Earthquake Hazards Reduction Program (NEHRP) soils data, and regional-MPO trip data in the form of Traffic-Analysis-Zone (TAZ) and Origin-Destination (OD) databases. The Import Wizard extracts information from these data sources and populates key fields of the link, node, bridge, and OD data tables. Detailed descriptions of the data sources are provided in this section.

The Import Wizard uses various data types to create a network study region. REDARS™ 2 requires an integrated network for analyzing post-earthquake traffic route and travel costs. Network data refers to the spatial data that replicates the real highway and street system (highway, arterials, and local streets) using a set of links and nodes. Nodes are points where traffic flow originates, terminates, or transmits, and links are the conduits for the flow between nodes. Such a node-link network model uses a linearly referenced data structure and maintains both connectivity and real-world properties (location, capacity, free flow speed, etc). The following discussion describes the data elements of the network and examines their sources.

B.4.1 Roadway Transportation Network

The Import Wizard uses the NHPN and HPMS national highway databases to model the spatial configuration and attributes of the highways and roadways in the study area.

B.4.1.1 National Highway Planning Network (NHPN) Database

The NHPN is a spatial network database for highways and major arterials. The data in this database are collected by the states and maintained by FHWA, and are in files that are in a zipped ARC/INFO© Interchange (.e00) format. REDARS™ 2 requires spatial network data for the roadway system to be in this format. NHPN Metadata are available from the following website: http://www.fhwa.dot.gov/planning/nhpn/docs/metadata.html. Further information on the NHPN database is provided in Cho et al. (2006a).

B.4.1.2 Highway Performance Monitoring System (HPMS) Database

The HPMS is a FHWA database of highway network attribute data that reflects the extent, condition, performance, use, and operating characteristics of the highways. HPMS files are delimitated text file with a metadata in a schema file (a text file). This database also contains Linear Referencing System (LRS) that can be used to associate attributes with the spatial elements of the NHPN database. HPMS data and documentation can be obtained from the following website: http://www.transtats.bts.gov/DataIndex.asp.

B.4.2 <u>Bridges</u>

REDARS™ 2 requires input data for all bridges in the roadway system. These data define each bridge's location, geometry, structural attributes, age, lanes, etc., in order to estimate bridge damage states, and associated repair costs, repair times, and traffic states during repairs (see Appendix G for further description of the input data needed for the REDARS™ 2 default bridge model.) In the REDARS™ 2 Import Wizard, a linearly referenced data structure makes it possible to integrate the bridge locations into the street network. Bridge placement along the roadway links is achieved through dynamic segmentation.

The FHWA National Bridge Inventory (NBI) database is the source of bridge data for the REDARS™ 2 Import Wizard (FHWA, 2003). This database contains data supplied by the states, in order to form a complete inventory of the number and condition of the nation's bridges on public roads that can be periodically reported to the Congress. It is intended for use by State, Federal and local agencies, and is maintained in a format prescribed by the "Recording and Coding Guide" for the Structure Inventory and Appraisal of the Nation's Bridges. The NBI database is made available to the public, usually in a delimited text file format, through the FHWA Office of Bridge Technology.

The NBI database is intended to facilitate assessment of the need for replacement and rehabilitation of the Nation's bridges. It was not developed to provide structural attribute information that would ordinarily be required to assess the seismic performance of these bridges. However, because the NBI database is currently the only electronic database of bridges nationwide, it is necessary to use this database in REDARS™ 2 in order to approximately deduce information needed for bridge seismic performance evaluation. Appendix G describes just what NBI data are used for this purpose, and how they are applied in the default bridge models currently included in REDARS™ 2. Further extensions of the current NBI database to provide more complete information needed for seismic analysis of bridges have been proposed and are currently under consideration (Yashinsky, 2005).

B.4.3 <u>Soils</u>

In order to assess effects of local soil conditions on site-specific ground motions at each roadway component site, the ground-motion models that are currently included in REDARS™ 2 require soils data based on the National Earthquake Hazard Reduction Program (NEHRP) soil-type classification. The Import Wizard accommodates such data if: (a) the digital 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 the NHPN base data, which are currently in NAD 1927.

In addition to the above soils data for estimating ground motion hazards, REDARS™ 2 requires data for estimation of site-specific liquefaction hazards. These data are not readily available in a national electronic database. Rather they must be developed separately by the REDARS™ 2 user through: (a) geologic screening of the soil conditions throughout the roadway network being analyzed, in order to identify those component sites that may be prone to liquefaction during an earthquake; and (b) for those sites, estimation of soil-layer properties that are needed as input to the liquefaction-hazard model currently included in REDARS™ 2. Chapter 4 provides more information on these particular input data requirements.

B.4.4 Transportation Analysis Zones (TAZs)

In order to enable local and state governments to monitor user trip demands on the highway-roadway system (particularly in terms of journey-to-work and place-of-work statistics), the region surrounding the system is subdivided into a set of subregions named Traffic Analysis Zones (TAZs). TAZ files are usually available from the local Metropolitan Organizations (MPOs). The REDARS™ 2 Import Wizard requires that the TAZ file be provided in ESRI Shapefile format within a geographic coordinate system. The datum must match the NHPN base data, which is currently in NAD 1927.

B.4.5 Origin-Destination (O-D) Trip Tables

An origin-destination (O-D) trip table (or O-D matrix) is a two-dimensional table that defines the number of trips from each TAZ in the surrounding region to all other TAZs in the region. O-D trip tables are input as a matrix of trips, and the Import Wizard requires the O-D file to be a tab, comma or space delineated TXT file that consists of the following columns:

- Column 1: Zone number for the TAZ that is the origin of this set of trips.
- Column 2: Zone number for the TAZ that is the destination for this set of trips.
- Columns 3, 4, 5…n: Number of trips between the zone-pair, grouped by trip types. That is, column 3 would include the number of automobile trips between the zones, and columns 4, 5, etc. would include the number of Freight Type 1, 2, etc. trips between the zones.

These O-D trip-table data are typically available through the MPO for the region.

B.5 IMPLEMENTATION STEPS

The following data importing steps are implemented when a user creates a study region using the Import Wizard:

B.5.1 Step 1: Create Blank Database Files Set

In Step 1 of the database creation process, the Import Wizard creates five Microsoft Access Database (MDB) files. These consist of the three distinctive MDB files contained in the REDARS™ 2 core program -- which are named RDF (REDARS™ Data File), RVB (REDARS™ Visual Basic for Application), and RPR (REDARS™ PRobabilistic Analysis) -- plus two additional temporal MDB files generated by the Import Wizard. Instead of relying on ADOX (Active Data Object Extension) for manipulating MDB file structure (including creation of the files), the individual files are created by “melting” binary files that contain all of the required data structure. This “melting” method is convenient since it does not require changing the program code to accommodate changes in data or database structure during development of REDARS™ 2.

B.5.2 Step 2: Populate HPMS Tables

The HPMS (Highway Performance Monitoring System) files are comma delimitated text file with a metadata in a schema file (a text file). The Import Wizard reads the metadata file to capture the data structure, including data field name and field length. A text parser in the Import Wizard reads the required data and populates tables in the temporary Import Wizard file.

B.5.3 Step 3: Populate NBI Tables

The bridge data from the NBI (Nation Bridge Inventory) database is also delivered in a column-based text file without delimiting characters. A text parser in the Import Wizard reads the file according to a pre-defined structure.

B.5.4 Step 4: Create and Populate NHPN Tables

The roadway system spatial data from the NHPN (National Highway Planning Network) are delivered in an uncompressed ArcInfo export file, e00. The Import Wizard reads the state-wide NHPN file, and populates the temporal Import Wizard tables for arc geometry, arc attributes, node attributes, route information, and linear referencing system.

B.5.5 Step 5: Establish Relationships between Tables and Create LINK Table

The Import Wizard creates two separate link tables -- one is for a region-wide network analysis that is carried out under Step 11, and the other is for the study area that is specified by the user. The region-wide link table is created by the following series of queries:

- Identify nodes within the Transportation Analysis Zone Map (TAZ).
- Identify links, of which any end-node is included in the node-set identified in the previous step.
- Identify “outside” nodes which are not within the TAZs, but are end-nodes of the selected links.
- Update the attributes of the selected links using HPMS attribute data.
- Add virtual links to connect the TAZ centroids to the selected nodes.

The link table for the selected study area is created from the HPMS-updated region-wide link table as follows:

- Identify nodes within the user-drawn boundary.
- In addition, identify nodes in the selected TAZs from the user-drawn boundary.
- Identify links, for which any end-node is included in the node set that was identified in the two previous steps.
- Identify “outside” nodes, which are nodes that are not within the user-drawn boundary, or within selected TAZs, but are instead end-nodes of the selected links.

- Add new virtual links to connect the centroids of the selected TAZs to the nodes in the study area.
- Create virtual links to connect adjacent "outside" nodes.
- Update the external virtual links between adjacent "outside" nodes to represent boundary conditions.

B.5.6 Step 6: Locate Bridges and Tunnels from NBI Database onto Links in LINK Table

Under Step 6, the data records in the NBI database are scrutinized to identify bridges and tunnels that are in the study area. The location of each bridge or tunnel in the study area is calculated through dynamic segmentation using a linear referencing system.

B.5.7 Step 7: Update Soil Type for Selected Highway Components

If NEHRP soils data are not available, REDARS™ 2 assumes that the soils at each component site correspond to NEHRP Type C default soil conditions (which can be overridden by the REDARS™ 2 user). These conditions are automatically stored in the Bridge, Tunnel, and Link tables in the RDF file. However, if NEHRP soils data for each component site are provided in the format described in Section B.4.1.3, Step 7 of this Import Wizard implementation procedure updates the Bridge, Tunnel, and Link tables by using a point-to-polygon relationship to replace the default soil conditions with the site-specific NEHRP site conditions.

B.5.8 Step 8: Subset TAZs and Calibrate Demand Functions

Under Step 8, the following calculations are carried out:

- ***Region-Wide Travel Times and Trip Demands.*** Apply the user-equilibrium network analysis procedure (App. C) to the region-wide network and O-D trip tables (Sec. B.4.1.5), assuming that the trip demands are fixed at their baseline (pre-earthquake) levels. Note that the region analyzed in this calculation extend beyond the study area whose seismic risks are to be analyzed using REDARS™ 2. Use this analysis to develop zone-to-zone travel time and partial trip-demand matrices[1] between the TAZs in this model that are beyond the study area. This step is time consuming because it involves very large network and OD trip-table matrices, and traces all routes throughout this network in order to count partial demand.
- ***Outside-Zone Travel Times and Trip Demands.*** Assuming that the travel times along the links between the outside-zones and the study area are infinite, and using the above partial trip demands for the outside zone only, compute the travel times for these trips. This gives the travel times on virtual links between "outside" nodes.

[1] This is termed a "partial trip-demand matrix", since it includes only those trips originating from the outside TAZs that also have destinations within these TAZs. The remaining trips from these outside TAZs (which are trips that end in TAZs within the interior study area rather than within the surrounding outside TAZs) are excluded from the partial trip demand matrices.

- ***Decay Function***. Develop parameters for estimation of how trip rates vary with travel time by regressing the pre-earthquake O-D trip-table data against the travel-time matrix, using an exponential function.
- ***Calibrated Demand Function Parameters.*** Apply the Deming-Stephan-Furness algorithm for balancing the gravity model that includes the above decay function, in order to calibrate the parameters needed to estimate how post-earthquake trip demands are affected by travel-time delays.

B.5.9 Step 9: Populate Database with Data for Study Area

All processes up to this current step are done using the temporal MDB file. The current step populates the Link, Node, and Shape Points tables considering the virtual links, new node IDs, new link IDs, and geographic objects.

B.5.10 Step 10: Bridge / TAZ / VARS Tables / Clean Up

The remaining tables are populated by importing selected data from the temporal MDB file. Actual updating of link attributes is done through data transaction. Scratch tables, and files are cleaned up. TAZ tables are created according to the OD file.

B.5.11 Step 11: Baseline Analysis

During the creation of the RDF file, the Import Wizard performs a network analysis of a larger baseline (pre-earthquake) regional network roadway system that includes the study area to be analyzed REDARS™ 2. In this, analysis all links in the network are 100% functional. The link and TAZ tables are then populated with the calibrated demand function parameters. Once everything is arranged in the RDF file, Import Wizard performs the baseline analysis. This analysis provides pre-earthquake travel-times and traffic volumes for the selected study area that will be compared to the post-earthquake values of these quantities as obtained from the subsequent REDARS™ 2 SRA of the study area.

The Import Wizard's overall running time will depend on the size of the region-wide TAZ, since this size defines the time needed to: (a) calibrate the demand function; and to also (b) subset the OD data for the REDARS™ 2 SRA study area from the larger regional network considered in the above baseline analysis. The size of the study area (number of TAZs selected and geographic area) is also important because the number of highway-roadway components (roadway links and nodes, bridges, and tunnels) is also related to the study area. The Import Wizard takes about 45-to-55 minutes to process 3,217 Southern California TAZs, and about 10 minutes to process TAZs for a small section of the northern San Francisco Bay Area that was considered in the beta testing of REDARS™ 2.

B.6 SCREENS

The following pages provide Import Wizard screen displays and brief descriptions of each of the steps required by the user to develop REDARS™ 2 input data.

When the REDARS™ 2 Import Wizard is first opened, the "Introduction" screen (Fig. B-2) provides a brief description of the steps required to create a REDARS™ 2 study region .

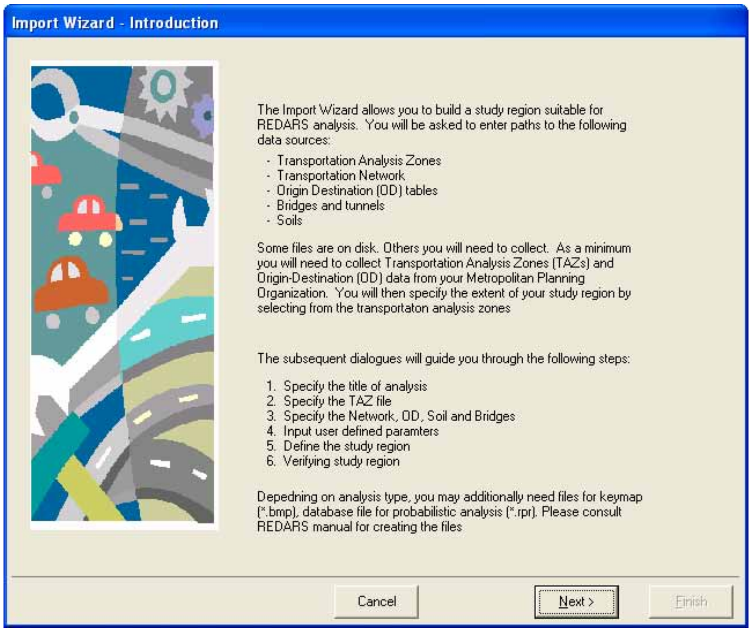


Figure B-2. Introduction Screen for REDARS™ 2 Import Wizard

This screen (Fig. B-3) allows the user to specify a name for the study region and a name for the REDARS™ 2 database file.

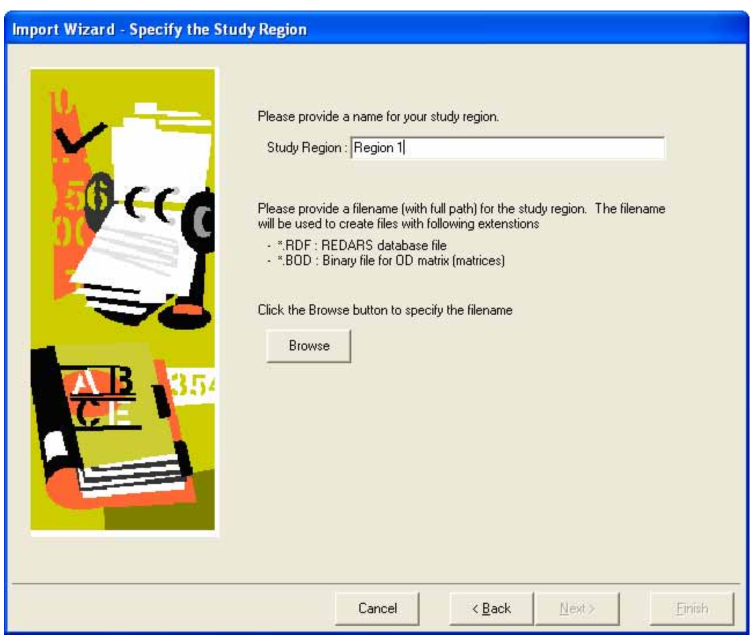


Figure B-3. Screen to Specify Study Region Name and REDARS™ 2® Database Filename

This screen (Fig B-4) allows the user to specify the location of NHPN and HPMS data files on disk. The Import Wizard reads and converts NHPN and HPMS data files to create a transportation network for use with REDARS™ 2.

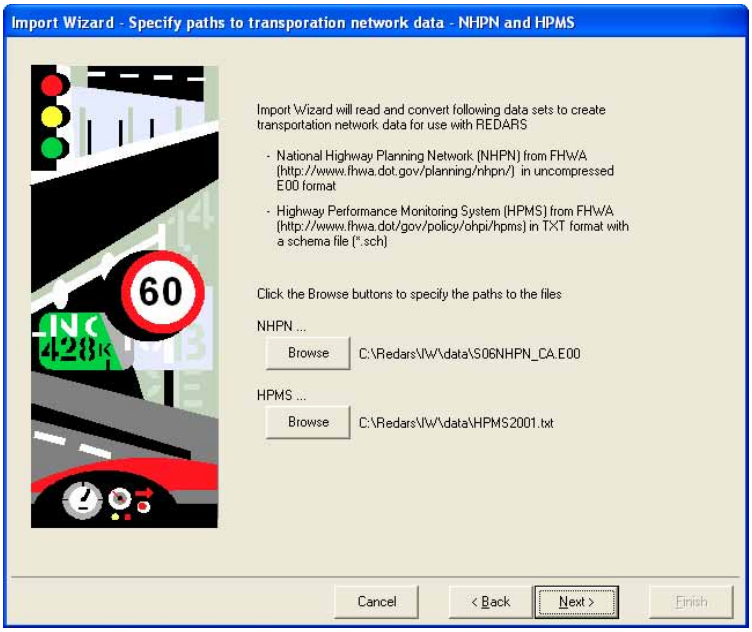


Figure B-4. Screen to Specify Paths to Network Data: NHPN and HPMS

This screen (Fig B-5) allows the user to specify the paths to the NBI bridge data files and NEHRP soil data files on disk. The Import Wizard reads the NBI bridge data file and locates the bridges on the transportation network for use with REDARS™ 2.

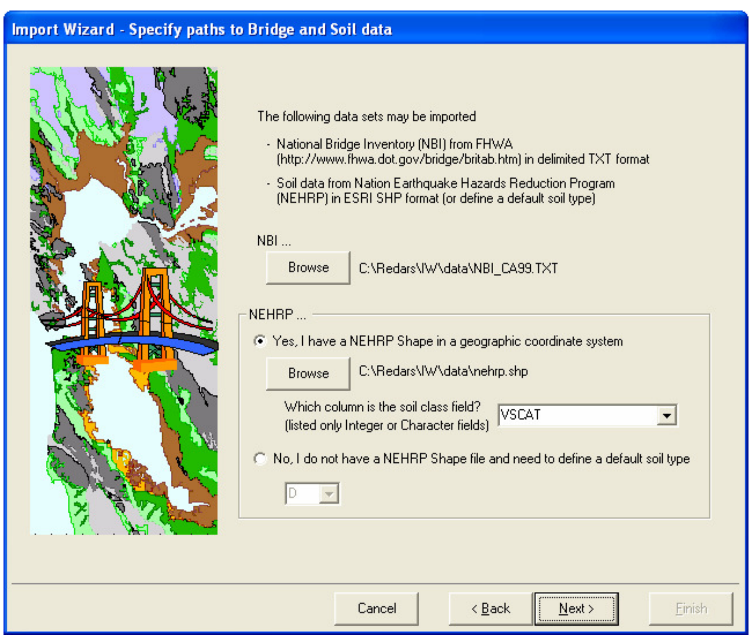


Figure B-5. Screen to Specify Paths to Bridge and Soil Data

This screen (Fig B-6) allows the user to specify the path to the Traffic Analysis Zone (TAZ) data file on disk. Traffic Analysis Zone (TAZ) files are usually available from the local Metropolitan Organizations (MPO).

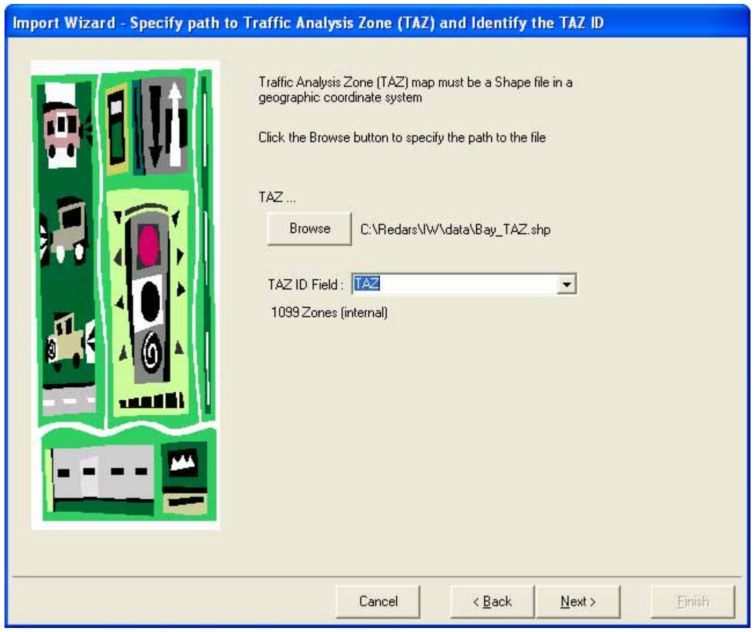


Figure B-6. Screen to specify path to TAZ data and identify TAZ ID field

This screen (Fig B-7) allows the user to specify the Origin Destination (OD) file on disk. OD files are usually available from the local Metropolitan Organizations (MPO).

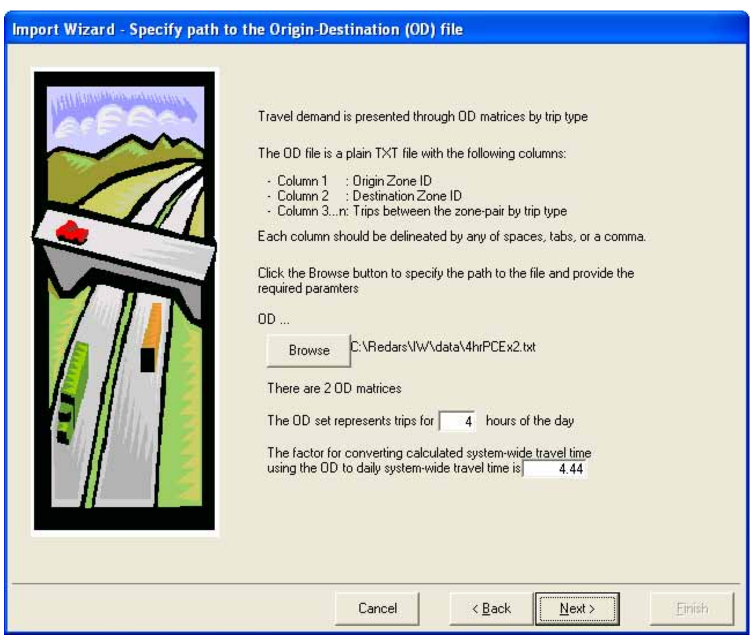


Figure B-7. Screen to Specify Path to OD Data

This screen (Fig B-8) allows the user to enter information on the Origin Destination (OD) parameters.

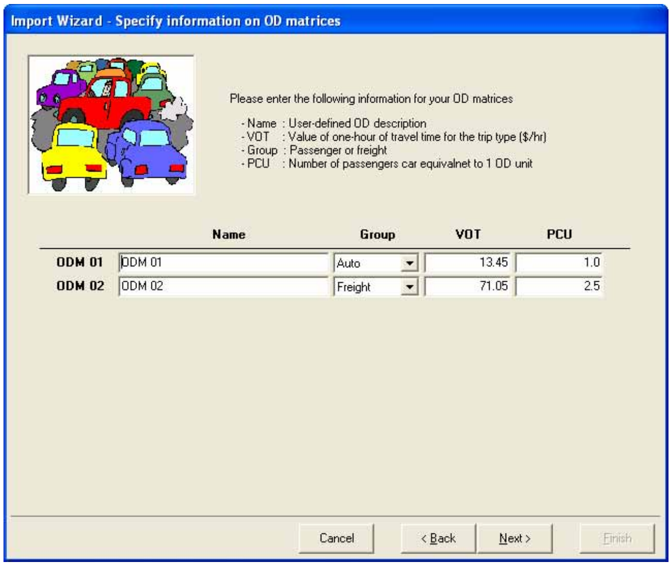


Figure B-8. Screen to Specify Information on OD Matrices

This screen (Fig B-9) is used to select the study region. It displays the transportation network overlaid on the TAZ map. A toolbar with standard GIS tools (zoom, pan, select) is available to the user to navigate the map and select the study region interactively. The TAZs are selected by drawing a polygon on the interactive map using the “Select TAZ” tool (see Fig.B-5). After drawing the study region, the user clicks the “Finish” button to start the data import process.

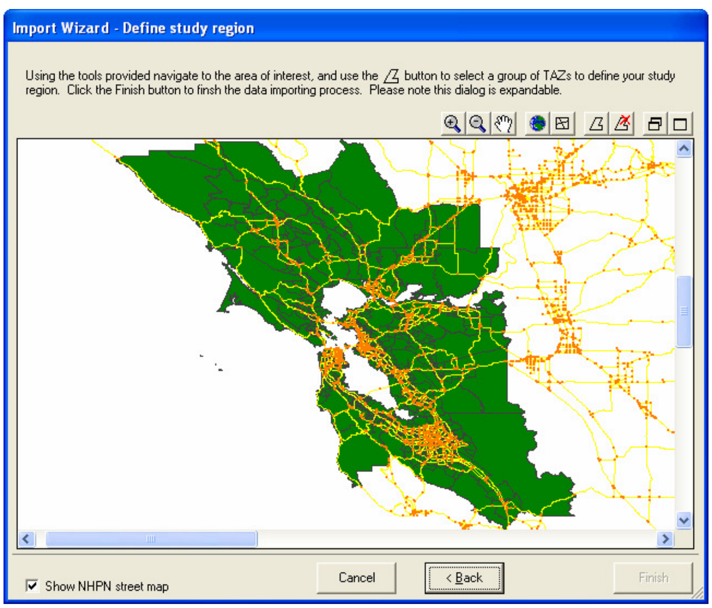


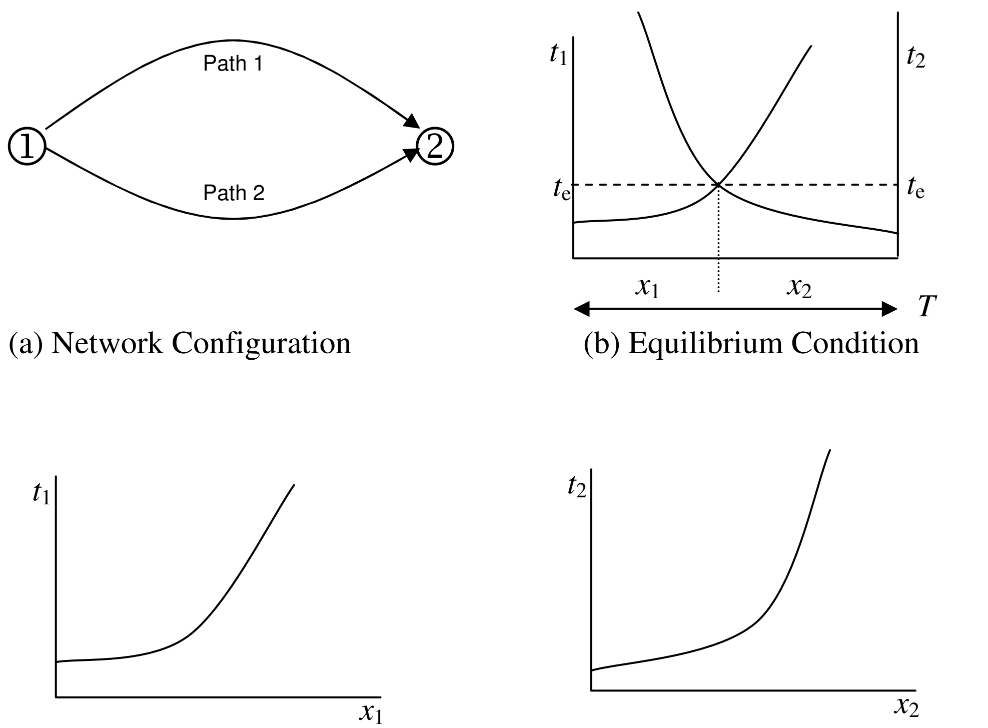
Figure B-9. Screen to Define Study Region Boundary

APPENDIX C
POST-EARTHQUAKE TRIP REDUCTION AND UPDATED MINIMUM-PATH ALGORITHM IN NETWORK ANALYSIS PROCEDURE

C.1 USER-EQUILIBRIUM MODEL WITH FIXED TRIP TABLE

Modern transportation network models are based on the Wardrop's rules of network equilibrium (Wardrop, 1952, recited from Sheffi 1985). According to these rules, the travel times along the *used* paths in a network are shorter than the travel times along the *unused* path and, in addition, individual drivers can not improve their driving time by altering their route. Thus, "user-equilibrium models" are models that estimate travel time and link volumes according to these Wardrop's rules. Based on the conceptual developments of Beckmann, et.al. (1956), Frank and Wolfe (1956) developed an efficient user-equilibrium solution algorithm that could be applied to a large-scale transportation network.

To illustrate, a simple transportation network is used here to derive the mathematical formulation of network equilibrium. In this, a total of T drivers will travel from Zone 1 to Zone 2 along Paths 1 and 2, as shown in Figure C-1a. In Figure C-1b, x_i, and t_i represent the traffic volume and travel time respectively along Path i.



(a) Network Configuration

(b) Equilibrium Condition

(c) Path 1 Congestion Function

(d) Path 2 Congestion Function

Figure C-1. Simple Network for Demonstration of Equilibrium Condition

To represent congestion, the travel time t_i is represented as a convex function of traffic volume. The resulting congestion functions for Path 1 and 2 are shown graphically in Figures C-1c and C-1d. At equilibrium, the travel time along both paths should be identical. This is shown in Figure C-1b, in which the total number of drivers, T is divided into traffic volumes, x_1 and x_2, according to the equilibrium travel time, t_e. Many researchers have proven that the area beneath these two congestion functions is minimized for a given travel demand T, when the trips are divided in such a way that the travel times on Path 1 and 2 are identical. From this, the user-equilibrium network model has following mathematical form:

$$\max\ z(\mathbf{x}) = \sum_a \int_0^{x_a} t_a(w)\ \ dw \tag{C-1}$$

subject to

$$\sum_k f_k^{rs} = q_{rs} \qquad \forall r, s \tag{C-2}$$

$$f_k^{rs} \geq 0 \qquad \forall k, r, s \tag{C-3}$$

$$q_{rs} \geq 0 \qquad \forall r, s \tag{C-4}$$

$$x_a = \sum_{rs} \sum_k f_k^{rs} \cdot \delta_{a,k}^{rs} \quad \forall a \tag{C-5}$$

where

t_a : link performance function of link a.

f_k^{rs} flow on path k connecting OD pair r-s.

q_{rs}: travel demand 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.

C.2 FORMULATION AND SOLUTION STEPS FOR VARIABLE-DEMAND MODEL

Going beyond the user-equilibrium model, the variable-demand model was developed to estimate link volumes, link travel times, and travel demands that satisfy the equilibrium condition. At equilibrium, the travel time on all used paths between any origin-destination zone pair are equal, and are less than the travel times on any unused paths. In addition, trip rates between an origin and destination are consistent with travel time, as calculated by a given demand function. These conditions define the user-equilibrium model with variable demand, whose mathematical form is as follows:

$$\max\ z(\mathbf{x}, \mathbf{q}) = \sum_a \int_0^{x_a} t_a(w)\ \ dw - \sum_{rs} \int_0^{q_{rs}} D_{rs}^{-1}(w)\ \ dw \tag{C-6}$$

subject to

$$\sum_k f_k^{rs} = q_{rs} \qquad \forall r,s \tag{C-7}$$

$$f_k^{rs} \geq 0 \qquad \forall k,\, r,s \tag{C-8}$$

$$q_{rs} \geq 0 \qquad \forall r,s \tag{C-9}$$

$$q_{rs} = D_{rs}(u_{rs}) \qquad \forall r,s \tag{C-10}$$

$$x_a = \sum_{rs}\sum_k f_k^{rs} \cdot \delta_{a,k}^{rs} \qquad \forall a \tag{C-11}$$

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.

The first term on right-hand side of Equation C-6 represents link volumes and travel times that satisfy the user-equilibrium model. The second term adjusts the travel-demand rates between zone-pairs such that the loaded travel demand on the network is consistent with its travel time.

Evans (1976) and Florian et al (1976) separately used the secant method to develop the algorithm to solve the above system of equations. This algorithm is basically identical to the algorithm used to represent the conditions of the user-equilibrium model for fixed travel demands, except that it includes the additional step of finding an auxiliary trip rate in Step 2.

Step 0: Initialization.

Find an initial feasible flow pattern $\{x_a^n\}$, $\{q_{rs}^n\}$. Set *n*:=1.

Step 1: Update Link Travel Time and Time Associated with Trip Making

Set $t_a^n = t_a(x_a^n)\ \forall a$; compute $D_{rs}^{-1}(q_{rs}^n)\ \forall r,s$.

Step 2: Find Auxiliary Link Volume and Trip Rate

Compute the shortest path, *m*, between each O-D pair *r-s* based on link travel time $\{t_a^n\}$, $c_m^{rs^n} = \min_{\forall k}\{c_k^{rs^n}(t_a^n)\}$

Find auxiliary trip rate

If $c_m^{rs^n} < D_{rs}^{-1}(q_{rs}^n)$, set $g_m^{rs^n} = \overline{q_{rs}}$ where *m* is shortest path, and $\overline{q_{rs}}$ is upper bound of trip rate

If $c_m^{rs^n} > D_{rs}^{-1}\left(q_{rs}^n\right)$, set $g_k^{rs^n} = 0 \ \forall k$

If $\left| c_m^{rs^n} - D_{rs}^{-1}\left(q_{rs}^n\right)\right| < \varepsilon$, set $g_m^{rs^n} = g_m^{rs^{n-1}}$

Auxiliary link volume $y_a^n = \sum_{rs}\sum_k g_k^{rs^n} \cdot \delta_{a,k}^{rs} \ \forall a$

Auxiliary trip rate $v_{rs}^n = \sum_k g_k^{rs^n} \ \forall r, s$

Step 3: Find Best Moving Step

Solve following system for *α*.

$$\min z(\alpha) \sum_a \int_0^{x_a^n + \alpha\left(y_a^n - x_a^n\right)} t_a(w)dw \ - \sum_{rs} \int_0^{q_{rs}^n + \alpha\left(v_{rs}^n - q_{rs}^n\right)} D_{rs}^{-1}(w)dw$$

subject to $0 \le \alpha \le 1$

Step 4: Flow Update

$$x_a^{n+1} = x_a^n + \alpha_n\left(y_a^n - x_a^n\right)$$

$$q_{rs}^{n+1} = q_{rs}^n + \alpha_n\left(v_{rs}^n - q_{rs}^n\right)$$

Step 5: Convergence Test

If following inequality holds for very small *κ*, terminate. Otherwise, set *n*:=*n*+1 and go to Step 1.

$$\sum_{rs} \frac{\left| D_{rs}^{-1}\left(q_{rs}^n\right) - u_{rs}^n\right|}{u_{rs}^n} + \sum_{rs} \frac{\left| u_{rs}^n - u_{rs}^{n-1}\right|}{u_{rs}^n} \le \kappa$$

C.3 ECONOMIC LOSS DUE TO EARTHQUAKE DAMAGE TO ROADWAY SYSTEM

Earthquake damaged transportation systems experience increased congestion and reduced trips. To represent the effects of increasing congestion, the difference between total travel times spent by drivers under pre- and post earthquake conditions, *λ* is calculated from Equation (C-12). In this, computation of the total travel time in the congested system is based on links (Equation C-12 a) as well as zone-pairs (Equation C-12b). The zone-to-zone travel time, c_{ij}, is computed as the sum of link travel times along the route between the zone pair. Again, under conditions of equilibrium, all routes between a zone-pair should have an identical travel time.

$$\lambda = \sum_a x'_a \, t'_a(x'_a) - \sum_a x_a t_a(x_a) \qquad \text{(C-12a)}$$

$$= \sum_i \sum_j \left(q_{ij} \cdot c_{ij} - q'_{ij} \cdot c'_{ij}\right) \qquad \text{(C-12b)}$$

where

x_a : volume on link *a* in intact network (pre-earthquake)

t_a : travel time on link a in intact network (pre-earthquake)
x'_a : volume on link a in damaged network (post-earthquake)
t'_a : travel time on link a in damaged network (post-earthquake)
q_{ij} : trips from zone i to zone j in intact network (pre-earthquake)
c_{ij} : travel time zone i to zone j in intact network (pre-earthquake)
q'_{ij} : trips from zone i to zone j in damaged network (post-earthquake)
c'_{ij} : travel time zone i to zone j in damaged network (post-earthquake)

The calculation of economic loss due to forgone trips, φ is

$$\varphi = \sum_i \sum_i \left(\int_{c_{ij}}^{c'_{ij}} D(w)\, dw \right) - \lambda \tag{C-13}$$

where

c_{ij} : travel time zone i to zone j in intact network (pre-earthquake)
c'_{ij} : travel time zone i to zone j in damaged network (post-earthquake)
D : the demand function, $q_{ij} = D(c_{ij})$, $q'_{ij} = D(c'_{ij})$

C.4 SAMPLE CALIBRATION OF DEMAND FUNCTION

Travel demand is endogenous in the VDM, and modeled by demand functions. In the following exercise, the demand function is based on Equation C-14. The number of trips between two zones is proportional to the total trips generated from the origin O_r, and total trips reaching the destination D_s. On the other hand, the trips are inversely related to the travel time, c_{rs}. This logic is similar to the gravity model, in which the interaction between two objects is proportional to the mass and inverse to the distance squared. Because of this similarity, the demand function is also called the gravity model.

$$q_{rs} = \frac{O_r \cdot D_s \cdot A_r \cdot B_s}{1 + \exp(\alpha + \beta \cdot c_{rs})} \tag{C-14}$$

where

q_{rs}: trip rate between OD pair r-s.
c_{rs}: travel time between OD pair r-s.
O_r: trip production from origin zone r.
D_s: trip attraction to destination zone s.
A_r: coefficient to be estimated associated with origin zone r.
B_s: coefficient to be estimated associated with destination zone s.
α, β: model parameters to be estimated.

In the VDM, the demand function is bounded by a maximum value of $O_r \cdot D_s \cdot A_r \cdot B_s$. Even in cases where the travel time is close to zero, the trips estimated by the function is limited to this value.

Since the parameters α and β in Equation C-14 were not given, they were estimated by devising an iterative process. With an origin-destination (O-D) trip requirement matrix (q_{rs}) the user-equilibrium model estimated zone-to-zone travel time (u_{rs}), and an econometric model estimated α and β from O-D trip requirements and zone-to-zone travel times. For these travel times and estimated parameters α and β, the gravity model was used to estimate zonal coefficients (A_r, B_s). Once all unknowns were estimated, a new O-D trip requirement matrix (q_{rs}) was re-generated. These steps were repeated until the estimated parameters α and β were unchanged over successive iterations. Table C-1 shows α, β values at the end of each iteration, in which the last set of values was applied in the analysis.

Table C-1: Calibration of the Demand Function Parameters

Iteration	α	β	R^2 to MTC OD
1	2.452310	0.088682	0.71769
2	2.543508	0.081813	0.69403
3	2.537076	0.082275	0.69594
4	2.538349	0.082190	0.69564
5	2.538382	0.082190	0.69564
6	2.538378	0.082191	0.69564
7	2.538379	0.082193	0.69565
8	2.538371	0.082192	0.69565

C.5: NUMERICAL EXAMPLE OF VARIABLE-DEMAND MODEL

This section describes an application of the variable-demand model to a small synthetic transportation system. Its small size on this system enables display of calculation results in every step and for all variables. Results from this example are used to estimate social cost.

C.5.1 Base Data for Variable-Demand Model

The transportation system in this example (Figure C-1) includes five links, labeled by L_a, and four traffic zones, Z_r. In this, the link L_2 is used by all three zone pairs in the system. Travel between zones Z_1 and Z_4 can occur along routes through L_1, and L_4+ L_2. For travel between zones Z_2 and Z$_4$, only link L_4 is used. $t_i(x)$ represents the congestion function for Link, L_a, which defines travel time for given traffic volumes along each link. The following function is used for this purpose, along with assumed traffic capacities and free-flow travel times.

$$t_1(x) = 10 \cdot \left(1 + 0.15 \cdot \left[\frac{x}{8}\right]^4\right),\ t_2(x) = 7 \cdot \left(1 + 0.15 \cdot \left[\frac{x}{12}\right]^4\right),\ t_3(x) = 9 \cdot \left(1 + 0.15 \cdot \left[\frac{x}{6}\right]^4\right),$$

$$t_4(x) = 4 \cdot \left(1 + 0.15 \cdot \left[\frac{x}{3}\right]^4\right),\ t_5(x) = 4 \cdot \left(1 + 0.15 \cdot \left[\frac{x}{3}\right]^4\right)$$

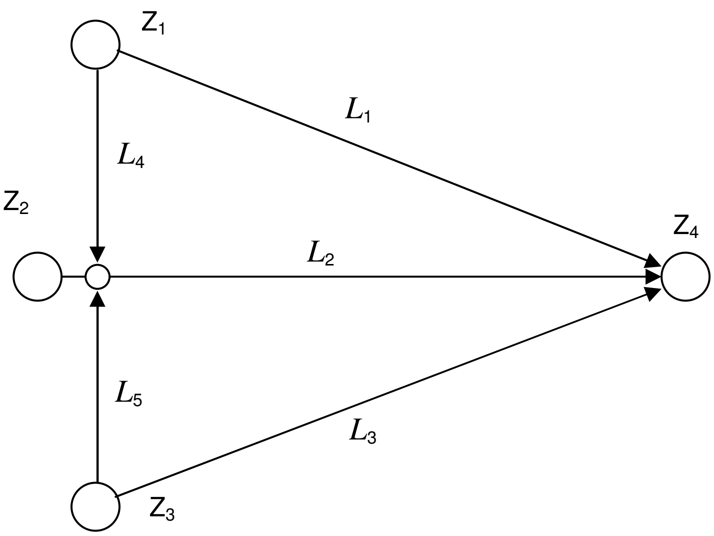


Figure C.2. Network Configuration for Numerical Example

Two types of travel demands originate from Zones Z_1, Z_2, and Z_3 and have zone Z_4 as their destination. Travel demand is modeled by the following demand functions D_{pq}^k, for each zone-pair. These functions are a simplified form of the demand function shown by Equation C-15. In REDARS™ 2, the parameters are calibrated by the Import Wizard, while this example assumes that the negative exponential function characterizes the decreasing demand over increasing travel time.

$$D_{14}^1 = 36.0 \cdot \exp(0.3 - 0.1 \cdot t_{14}) \qquad D_{14}^2 = 9.8 \cdot \exp(0.002 - 0.05 \cdot t_{14})$$
$$D_{24}^1 = 14.4 \cdot \exp(0.3 - 0.1 \cdot t_{24}) \qquad D_{24}^2 = 6.0 \cdot \exp(0.002 - 0.05 \cdot t_{24})$$
$$D_{34}^1 = 18.0 \cdot \exp(0.3 - 0.1 \cdot t_{34}) \qquad D_{34}^2 = 14.0 \cdot \exp(0.002 - 0.05 \cdot t_{34})$$

Note that the coefficients in the exponent are unique by trip types because those are usually calibrated for each OD matrix against travel time.

Maximum demand, $\overline{q}_{rs}$ is required in to calculate auxiliary demand, and is assumed as follows:

$$\overline{q}_{14}^1 = 20, \quad \overline{q}_{24}^1 = 9, \quad \overline{q}_{34}^1 = 12$$
$$\overline{q}_{14}^2 = 7, \quad \overline{q}_{24}^2 = 4, \quad \overline{q}_{34}^1 = 10$$

C.5.2 Solution Steps for the Variable-Demand Model

Based on this input data, detailed calculation steps from the first three iterations (0 to 2) are provided as follows.

Iteration 0

Step 0: Initialization

In the initial stage, all the link volumes and demands are assumed to be zero

	L_1	L_2	L_3	L_4	L_5
Volume, x_a	0.00	0.00	0.00	0.00	0.00

		Z_{14}	Z_{24}	Z_{34}
Demand, q_{rs}	Trip Type1	0.00	0.00	0.00
	Trip Type2	0.00	0.00	0.00

Step 1: Update Link Travel Time

This step applies the assumed link traffic volume (0 in Iteration 0) to the congestion function, in order to calculate link travel times (which in this case is the free-flow travel time)

	L_1	L_2	L_3	L_4	L_5
Time, $t_a^n = t_a(x_a^n)$	10.00	7.00	9.00	4.00	4.00

Step 2: Auxiliary Demand

The auxiliary demand is calculated by comparing the travel time along the shortest path, to the inverse of demand function, D^{-1}, which estimates corresponding travel time to the demand estimated from previous iteration. If the shortest travel time is less than the time from the inverse of the demand function, the auxiliary demand is set equal to the maximum demand, $\overline{q}_{rs}$. Otherwise it will be zero.

In Iteration 0, the demand is 0 and, as a result, the inverse of demand function results in an infinite time unit. Therefore, all auxiliary demands are equal to the maximum demand.

		Z_{14}	Z_{24}	Z_{34}
Time on shortest path $c_m^{rs^n} = \min_{\forall k}\left\{c_k^{rs^n}\left(t_a^n\right)\right\}$		10.00	7.00	9.00
D^{-1}	Trip Type1	∞	∞	∞
	Trip Type2	∞	∞	∞
Auxiliary Demand, v_{rs}	Trip Type1	20.00	9.00	12.00
	Trip Type2	7.00	4.00	10.00

Step 3: Auxiliary Link Volume

Auxiliary link volume is obtained by loading the auxiliary demand on to the current shortest path.

	L_1	L_2	L_3	L_4	L_5
Auxiliary volume, y_a	27.00	13.00	22.00	0.00	0.00

Step 4: Best Moving Step

The best moving step is calculated by solving the following one-dimensional optimization problem with respect to α .

$$\min z(\alpha) = \sum_a \int_0^{x_a^n + \alpha\left(y_a^n - x_a^n\right)} t_a(w)dw \; - \sum_{rs} \int_0^{q_{rs}^n + \alpha\left(v_{rs}^n - q_{rs}^n\right)} D_{rs}^{-1}(w)dw$$

However, for Iteration 0, α =1 is used to replace the assumed 0 demand, and 0 link volumes with the auxiliary demand and volumes.

Step 5: Update Flow

Since α =1 in Iteration 0, the updating is actually replacing the 0 demand, and 0 link volumes with the auxiliary demand and volumes.

		Z_{14}	Z_{24}	Z_{34}
Demand, q_{rs}	Trip Type1	20.00	9.00	12.00
	Trip Type2	7.00	4.00	10.00

	L_1	L_2	L_3	L_4	L_5
Link Volume, x_a	27.00	13.00	22.00	0.00	0.00

<u>**Iteration 1**</u>

Step 1: Update Link Travel Time

As non-zero link volumes are estimated from Iteration 0, travel times through the used links are very high.

	L_1	L_2	L_3	L_4	L_5
Time, $t_a^n = t_a\left(x_a^n\right)$	204.62	8.45	253.02	4.00	4.00

Step 2: Auxiliary demand

At the end of the prior iteration, the demand is set equal to the auxiliary demand, which is the same as the maximum demand, $\overline{q}_{rs}$. Thus, the inverse of the demand function, D^{-1}, provides possible lowest time units. On the other hand, some part of network is already congested. In this case, no travel times along shortest paths are less than D^{-1}, so all of the auxiliary demand is zero.

		Z_{14}	Z_{24}	Z_{34}
Time on shortest path $c_m^{rs^n} = \min_{\forall k}\{c_k^{rs^n}(t_a^n)\}$		12.45	8.45	12.45
D^{-1}	Trip Type1	8.88	7.70	7.05
	Trip Type2	6.77	8.15	6.77
Auxiliary Demand, v_{rs}	Trip Type1	0.00	0.00	0.00
	Trip Type2	0.00	0.00	0.00

Step 3: Auxiliary link Volume

Loading the zero auxiliary demand onto the shortest path yields zero auxiliary link volumes.

	L_1	L_2	L_3	L_4	L_5
Auxiliary volume, y_a	0.00	0.00	0.00	0.00	0.00

Step 4: Best Moving Step

Solving the following optimization problem with respect to α yields α=0.5256.

$$\min z(\alpha) = \sum_a \int_0^{x_a^n+\alpha(y_a^n-x_a^n)} t_a(w)dw - \sum_{rs} \int_0^{q_{rs}^n+\alpha(v_{rs}^n-q_{rs}^n)} D_{rs}^{-1}(w)dw$$

Step 5: Update Flow

Linearly combining the previous demand and volume with the auxiliary estimations for which α=0.5256 yields the following results. Up to this iteration, some links are not yet used, since their free flow travel times are longer than the congested travel times along other routes.

		Z_{14}	Z_{24}	Z_{34}
Demand, q_{rs}	Trip Type1	9.49	4.27	5.69
	Trip Type2	3.32	1.90	4.74

	L_1	L_2	L_3	L_4	L_5
Link Volume, x_a	12.81	6.17	10.44	0	0

<u>Iteration 2</u>

Step 1: Update Link travel time

The high link travel time estimated at the beginning of Iteration 1 dissipates as demand and volume are adjusted

	L_1	L_2	L_3	L_4	L_5
Time, $t_a^n = t_a(x_a^n)$	19.86	7.07	21.36	4.00	4.00

Step 2: Auxiliary Demand

As the path time reaches equalization, the travel time along the shortest path is less than D^{-1}. So, once again, the maximum demand, $\bar{q}_{rs}$ corresponds to the auxiliary demand.

		Z_{14}	Z_{24}	Z_{34}
Time on shortest path $c_m^{rs^n} = \min_{\forall k}\left\{c_k^{rs^n}\left(t_a^n\right)\right\}$		11.07	7.07	11.07
D^{-1}	Trip Type1	16.33	15.16	14.51
	Trip Type2	21.68	23.06	21.68
Auxiliary Demand, v_{rs}	Trip Type1	20.00	9.00	12.00
	Trip Type2	7.00	4.00	10.00

Step 3: Auxiliary Link Volume

	L_1	L_2	L_3	L_4	L_5
Auxiliary volume, y_a	0.00	62.00	0.00	27.00	22.00

Step 4: Best Moving Step

Solving the following optimization problem with respect to α, yields α =0.1647.

$$\min z(\alpha) = \sum_a \int_0^{x_a^n+\alpha\left(y_a^n - x_a^n\right)} t_a(w)dw - \sum_{rs} \int_0^{q_{rs}^n+\alpha\left(v_{rs}^n - q_{rs}^n\right)} D_{rs}^{-1}(w)dw$$

Step 5: Update Flow

Eventually, all of the five links are used by the demand. However, comparisons of the alternative path travel times show that the model has not yet converged. For example, for zone-pair Z_1-Z_4, the travel time on path L_4+L_2 is about twice (19.81 minutes) the travel time along Link L_1 (10.70 minutes).

		Z_{14}	Z_{24}	Z_{34}
Demand, q_{rs}	Trip Type1	11.22	5.05	6.73
	Trip Type2	3.92	2.24	5.60

	L_1	L_2	L_3	L_4	L_5
Link Volume, x_a	10.70	15.36	8.72	4.45	3.62

Table C-2 and C-3 summarize the zone-to-zone trip rates (travel demand), and travel time on shortest path resulted at the end of each iteration respectively.

Table C-2. Trip Rates Estimated by VDM for the Numerical Example

Iteration	Demand, q_{rs} ,Type 1			Demand, q_{rs} ,Type 2			Travel Time on Shortest Path			Moving step
	Z_{14}	Z_{24}	Z_{34}	Z_{14}	Z_{24}	Z_{34}	Z_{14}	Z_{24}	Z_{34}	
1	9.49	4.27	5.69	3.32	1.90	4.74	12.45	8.45	12.45	0.5256
2	11.22	5.05	6.73	3.93	2.24	5.61	11.07	7.07	11.07	0.1647
3	9.15	5.78	5.49	4.49	2.57	6.42	14.80	9.82	15.02	0.1845
4	9.68	5.94	5.81	4.62	2.64	6.60	13.69	9.51	14.08	0.0489
5	10.10	6.06	5.57	4.71	2.69	6.73	15.07	10.24	14.48	0.0404
6	10.33	6.13	5.72	4.60	2.72	6.81	15.04	10.15	14.64	0.0234
7	9.99	6.22	5.54	4.45	2.77	6.58	15.83	10.48	15.51	0.0329
8	10.18	6.28	5.66	4.50	2.79	6.65	15.10	10.39	14.69	0.0192
9	10.28	6.30	5.60	4.52	2.80	6.58	15.47	10.34	15.40	0.0101
10	10.41	6.34	5.53	4.56	2.82	6.50	15.48	10.55	15.15	0.0131
11	10.08	6.42	5.36	4.41	2.85	6.61	15.90	10.51	14.84	0.0313
12	10.22	6.46	5.45	4.45	2.87	6.65	15.19	10.43	14.95	0.0140
13	10.29	6.48	5.41	4.47	2.88	6.61	15.54	10.39	15.19	0.0070
14	10.39	6.50	5.35	4.50	2.89	6.54	15.48	10.53	15.30	0.0107
15	10.27	6.53	5.43	4.44	2.90	6.58	15.83	10.50	15.03	0.0114
16	10.09	6.57	5.33	4.49	2.92	6.46	15.56	10.47	15.18	0.0174
17	10.19	6.60	5.40	4.51	2.93	6.50	15.42	10.42	15.03	0.0094
18	10.22	6.61	5.42	4.52	2.94	6.51	15.53	10.40	15.04	0.0035
19	10.12	6.63	5.37	4.48	2.95	6.54	15.64	10.54	15.23	0.0097
20	10.20	6.65	5.42	4.50	2.96	6.57	15.43	10.59	15.05	0.0084
30	10.23	6.71	5.33	4.50	3.03	6.57	15.62	10.64	15.18	0.0066

Table C-3. Link Volume and Time Estimated by VDM for the Numerical Example

Iteration	Link Travel Time					Link Volume				
	L_1	L_2	L_3	L_4	L_5	L_1	L_2	L_3	L_4	L_5
1	204.62	8.45	253.02	4.00	4.00	12.81	6.17	10.44	0.00	0.00
2	19.86	7.07	21.36	4.00	4.00	10.70	15.36	8.72	4.45	3.62
3	14.80	9.82	15.02	6.89	5.28	10.02	14.92	8.96	3.63	2.95
4	13.69	9.51	15.70	5.28	4.56	10.85	15.91	8.52	3.45	3.89
5	15.07	10.24	14.48	5.05	5.69	11.50	15.79	8.58	3.31	3.73
6	16.41	10.15	14.64	4.89	5.43	11.23	16.19	8.89	3.70	3.64
7	15.83	10.48	15.51	5.39	5.30	10.86	16.09	8.60	3.58	3.52
8	15.10	10.39	14.69	5.21	5.14	11.17	16.03	8.86	3.51	3.45
9	15.70	10.34	15.41	5.12	5.05	11.06	16.27	8.77	3.75	3.42
10	15.48	10.55	15.15	5.46	5.01	11.27	16.23	8.65	3.70	3.37
11	15.90	10.51	14.84	5.38	4.96	10.91	16.13	8.69	3.58	3.27
12	15.19	10.43	14.95	5.22	4.85	11.14	16.08	8.88	3.53	3.22
13	15.64	10.39	15.48	5.15	4.80	11.06	16.25	8.82	3.70	3.20
14	15.48	10.53	15.30	5.38	4.78	11.23	16.22	8.72	3.66	3.17
15	15.83	10.50	15.03	5.32	4.74	11.10	16.18	8.88	3.61	3.13
16	15.56	10.47	15.47	5.26	4.71	11.03	16.12	8.72	3.55	3.08
17	15.42	10.42	15.03	5.18	4.66	11.18	16.09	8.85	3.52	3.05
18	15.72	10.40	15.38	5.14	4.64	11.14	16.26	8.81	3.60	3.11
19	15.64	10.54	15.29	5.25	4.70	11.03	16.32	8.73	3.57	3.18
20	15.43	10.59	15.05	5.20	4.76	11.17	16.29	8.84	3.54	3.15
30	15.62	10.64	15.18	5.14	4.71	11.24	16.35	8.78	3.50	3.11

C.6 UPDATING THE MINIMUM-PATH ALGORITHM

C.6.1 Background

In transportation network analysis, the vector of traffic volume on each link is unknown, and thus, the algorithm keeps improving link volume estimates, as Section C.2 describes. In Step 2 of the algorithm, the model searches paths from each zone to all other zones.. The path-search algorithm is optimized by using "one-to-all tree building", instead of searching zone combinations one-by-one, in which the algorithm searches one path that connects one "root" zone to all other zones, as a pattern like the branches of a tree. The path-search algorithm is repeated for as many iterations as there are zones multiplied by the number of time intervals analyzed. Sheffi (1985) measured the running time of transportation analysis model, and concluded about 95% of the running time is involved in the path search.

C.6.2 Previously Implemented Minimum-Path Algorithm

The pseudo code of the previously implemented algorithm is presented in Figure C-3. Given the root, r, the algorithm identifies an set of nodes ordered ascending by travel time. In this set, a given node, b_i, is the node that precedes the node *i* on the path from the root, so that trips from the root always traverse node *bi*, to reach node *i*. Therefore, b_i is the "From-Node" link, while *i* is the "To-Node" of the link. For this relationship, b_i is called *back-node* of node *i*. Unless isolated from the network, all nodes should have only one *back-node* after the algorithm is terminated. Also, a node has only one *back-node*, otherwise a node can be reached from the root node via more than one path.

The algorithm consists of four major steps – (1) initialization , (2) identifying a set of nodes accessible from a hub node (called forward-star. see Figure C-4 and the description below), (3) examination of the travel time to the forward-star nodes, and (4) maintaining the set of hub node S.

In this algorithm, node *i* in Figure C-4 is a selected as the hub node. From the hub node, travel time from the root to the "To-Nodes" of links, *j* are examined to see if the hub is the *back node*. . If the sum of travel time to the hub node (from root, c_{ri}) and link travel time (t_{ij}) is less than the current travel cost to *j*, the hub is the *back node* of the "To-Node" (Figure C-5, left). However, if the "To-Node" *j* has a lower travel time, (via another hub) the *back-node* remains unchanged, as illustrated in the right hand side of Figure C-5. This process is presented in Step 3 of the algorithm.

Initialize:

$S = \emptyset$

$b_i = \infty \quad \forall i \in N$

$c_i = \infty \; \forall i \in N$

r = Origin node (root of the tree) ....(1)

$i = r$

$b_i = 0$

$c_{ri} = 0$

InsertTail i into S

Start_Algorithm:

Pop i from S

$R_i = \{ j \in N \,|\, l_{ij} \in A \}$ ....(2)

Do loop for each node *j* in *R*

If $c_{rj} < c_{ri} + t_{ij}$ then

$c_{rj} = c_{ri} + t_{ij}$ ....(3)

$b_j = i$

If *j* has ever been in *S* but not in *S* now

InsertHead j into S

Else if *j* has never been in *S* ....(4)

InsertTail j into S

End if

End if

End Loop

If *S* is empty, terminate algorithm

Else go to *Start_Algorithm*:

Figure C-3: Pseudo-Code of Moore-Pape Minimum-Path Algorithm

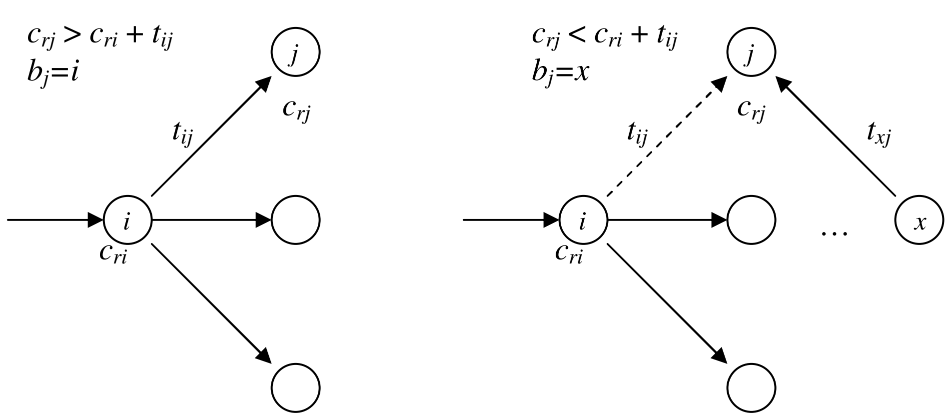


Figure C-4. Examination of Forward Star

R in Step 2 of the algorithm, is the set of node j, which consists of all the To-Nodes of the collection of links where the From-Node is the hub, as illustrated in Figure C-4. Sheffi (1985) refers to the set as a *forward-star* because of the shape of the subsystem and the directionality from the root to each destination. A typical transportation network contains less nodes than links, and finding a path by comparing travel time to nodes is more efficient than comparing link travel times from the root node. Therefore the algorithm performs repeated comparisons for each node in R until every node in the network system is examined.

Once examination from a hub node is completed, the algorithm requires specification of the next node that is to be used as the hub of examination. Whenever a lower travel cost for a node is identified (a new *back-node*), the node can be a hub in the next iteration because every node on the path can possibly be *back-node*. Therefore, one way to supply hub nodes in consecutive examinations is to have a temporary memory storage populated whenever the *back-node* of a node is updated. The set *S* in Step 4 of the algorithm is stored in this memory. In the Moore-Pape algorithm, *S* has special characteristics as discussed below that make the algorithm more efficient.

S is temporary data storage (or an array), generally referred to as the "queue". A queue is a unidirectional data storage model that is similar to a line in front of a teller window which is served under a first-in-first-out policy. Customers come into the queue through the tail and go out through the head. However, S is a special queue that has two entrances on both sides, and one exit from the side. Since it is a two-sided queue, data (candidates for the hub) are inserted into *S* through the head and tail, and data (the hub node for the next examination) pops out from the head of the queue. Elements in *S* are connected to adjacent elements. The head and tail of S are maintained by other complementary pointers in computer memory. Figure C-5 shows how to implement the structure of *S* in a computer, and the process of entering the queue (i.e., insertion) and exiting the queue (pop) that is used during examination of the hub.

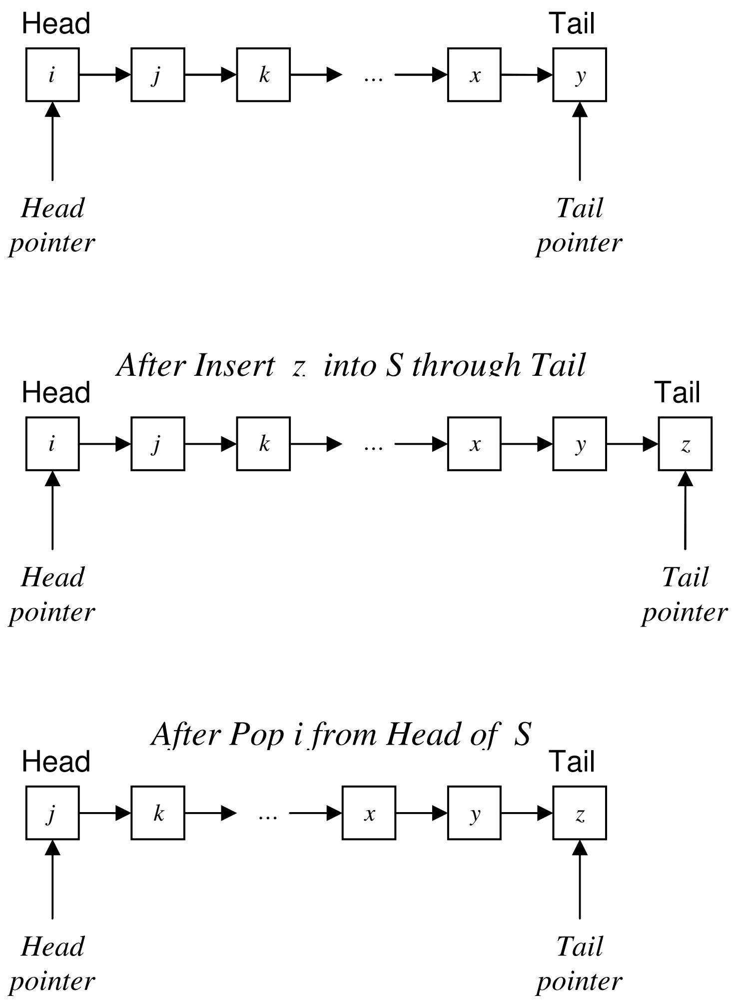
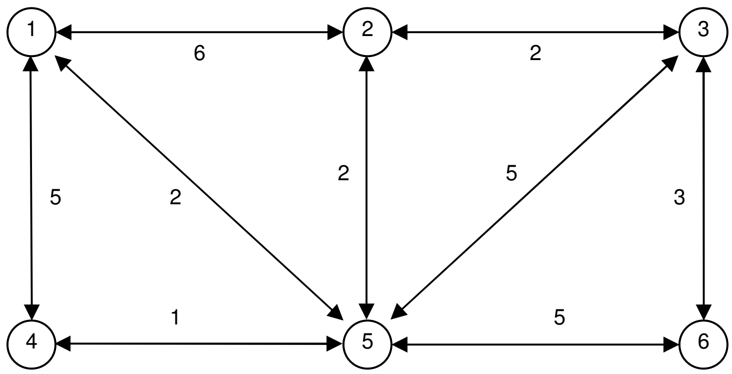


Figure C-5. Structure of S after Performing Insertion and Pop

To illustrate this process, a numerical example is provided. This example considers the network shown in Figure C-6 that has 6 nodes and 18 links. Node 1 is the root in this example. Each line presents bi-directional links.

Note that, from examination from hub node 5, nodes 2, 3, and 4 are reinserted into *S* because their new travel costs are lower than previous ones respectively. In the next examination, node is taken as hub. It is not because elements in *S* are sorted with respect to node ID, but because node 2 has been in S, and reinserted. Examination from hub 2 updates travel cost to node 3 again, and its *back-node*.

(a) Sample Network

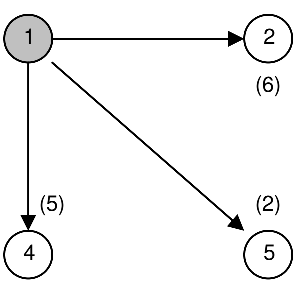


(b) Minimum Path Searching Steps

Initialization
Root = 1

Node	Cost to reach from node 1	Back-node
1	0	0
2	∞	∞
3	∞	∞
4	∞	∞
5	∞	∞
6	∞	∞

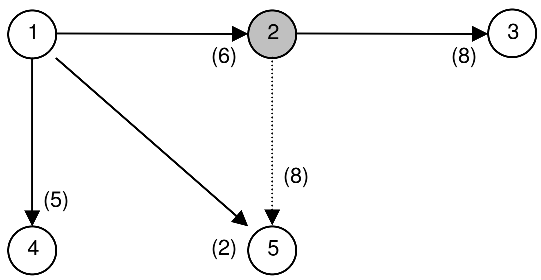
S={1}
Hub = 1 (cost to hub from root = 0)
R= {2, 4, 5}



Node	Cost to reach from node 1	Back-node
1	0	0
2	6	1
3	∞	∞
4	5	1
5	2	1
6	∞	∞

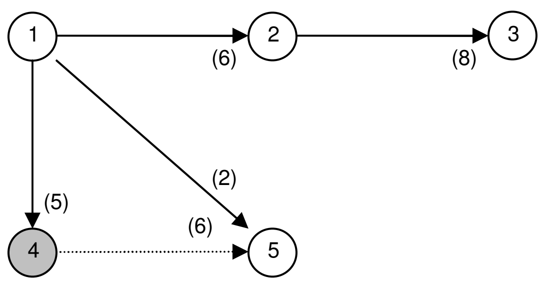
Figure C-6. Numerical Example of Moore-Pape's Minimum-Path Algorithm (Part 1 of 3)

$S = \{2, 4, 5\}$
Hub =2 (cost to hub from root = 6)
$R = \{1, 3, 5\}$



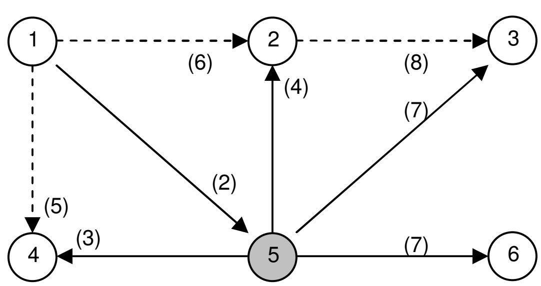
Node	Cost to reach from node 1	Back-node
1	0	0
2	6	1
3	8	2
4	5	1
5	2	1
6	∞	∞

$S = \{4, 5, 3\}$
Hub = 4 (cost to hub from root = 5)
$R = \{1, 5\}$



Node	Cost to reach from node 1	Back-node
1	0	0
2	6	1
3	8	2
4	5	1
5	2	1
6	∞	∞

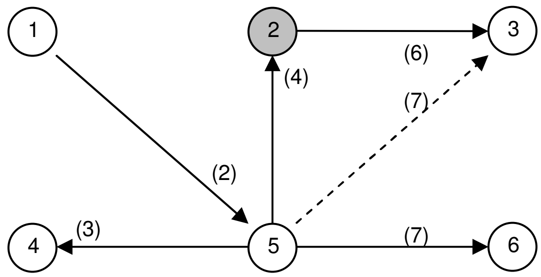
$S = \{5, 3\}$
Hub = 5 (cost to hub from root = 2)
$R = \{1, 2, 3, 4, 6\}$



Node	Cost to reach from node 1	Back-node
1	0	0
2	4	5
3	7	5
4	3	5
5	2	1
6	7	5

Figure C-6. Numerical Example of Moore-Pape Minimum-Path Algorithm (Part 2 of 3)

$S = \{2, 3, 4, 6\}$ (nodes 2, 3, 4 are reinserted into S through head because those were used once as hub node)
Hub = 2 (cost to hub from root = 4)
$R = \{1, 3, 5\}$



Node	Cost to reach from node 1	Back-node
1	0	0
2	4	5
3	6	2
4	3	5
5	2	1
6	7	5

$S = \{3, 4, 6\}$
Examinations from hub 3, 4, and 6 do not update any travel cost, or *back-node*

(c) Resulting minimum path rooted from node 1

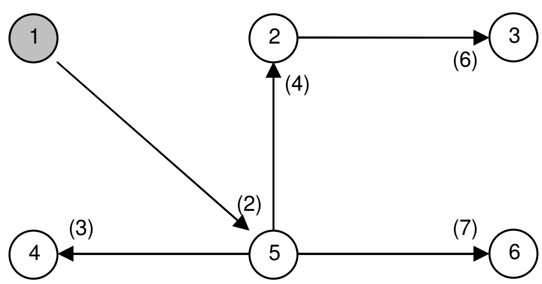


Figure C-6. Numerical Example of Moore-Pape Minimum-Path Algorithm (Part 3 of 3)

C.6.3 <u>Dual-Simplex Algorithm</u>

The Dual-Simplex method is a solution technique of linear programming. Linear programming is an optimization problem that consists of a linear objective function, linear constraints, and non negativity constraints, such as

$$\max \sum_i c_i \cdot x_i \qquad \text{(C-15)}$$
$$s.t.\ a_i \cdot x_i \le b_i \ , \ x_i \ge 0$$

In the solution process, the Dual-Simplex algorithm improves the objective function in two ways: a) from an optimization solution, it replaces an infeasible variable to improve feasibility; and b) from a feasibility solution, it replaces a variable to improve optimality.

Let us assume that Nodes *i* and *j* are adjacent zone centroids, as shown in Figure C-7. Once a path from Node *i* is established, the process goes to Node *j*. Node *i* is connected via links grouped in *a*. From Node *i*, Node *j* is connected via links grouped in *a*' to the main body of the path tree. Establishment of a path from Node *j* actually consists of the following steps:

- Step 1: Remove links that connect the prior root node to the main body of the tree (link group a).
- Step 2: Add links that connect the main body of the tree to the prior root node (link group b)
- Step 3: Remove the links that connect the main body of the tree to the new root node (link group a')
- Step 4: Add links that connect the new root node to the main body of tree (link group b')

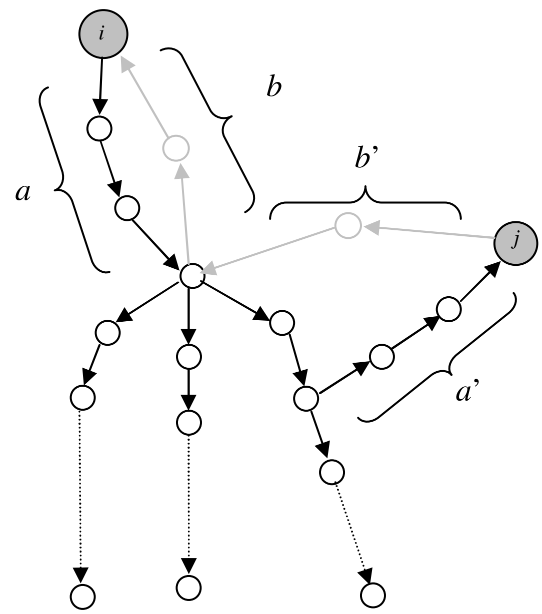


Figure C-7. Establishing Path from a New Root by Dual-Simplex Algorithm

Steps 1 and 3 are removing links to achieve feasibility, while Steps 2 and 4 increase optimality. Actually, the links in Group *a* and *a*' are examined one-by-one. Also, links in Group b and b' are identified simultaneously while identifying the so-called "main body" of the tree.

Identification of the main body of the tree should not be more costly than examination of all nodes and links according to the Moore-Pape algorithm. Faster identification of the main body of the tree is accomplished by 1) the tree-branch topology of the previous path; and 2) nodes connecting links in group *b* that are used to connect the previous root to the common path, and *b*' that connects the adjacent root to the common part of path. The topology of the previous path is stored in a special data structure that is specified by Dial et al. (1979).

C.6.4 Run-Time Comparisons

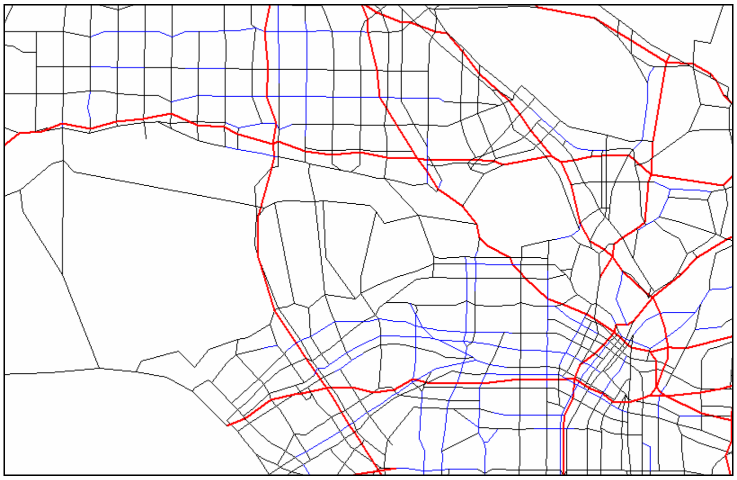
Both the Moore-Pape and Dual-Simplex algorithms are implemented in an OCX, and the CPU running time for the search paths are compared. Five different sets of transportation network data are used in this comparison.

- SCAG-1534 is a simplified version of the base network for a 1990 transportation survey of the five-county Southern California region. Consecutive links with similar attributes are merged..
- SCAG-3217 is the original form of the base transportation network for the 1996 supplement survey.
- SCAG-1470 is a simplified version of SCAG-3217. Instead of merging links, zones are merged in this case. The centroids of the merged zones are connected to nodes that were zone centroids in SCAG-3217 system. Thus, 1470 nodes and 6434 (2*3217) links were added.
- LA-480 is developed from the SCAG-1534 and NHPN databases. It covers the area that was affected by the 1994 Northridge Earthquake, including downtown Los Angeles. Its zone system follows SCAG-1534.
- Bay-1120 is the base transportation network database (as of 1998) for the San Francisco Bay area, posted on the website of the Metropolitan Planning Commission, who is the Metropolitan Planning Organization (MPO) for the region

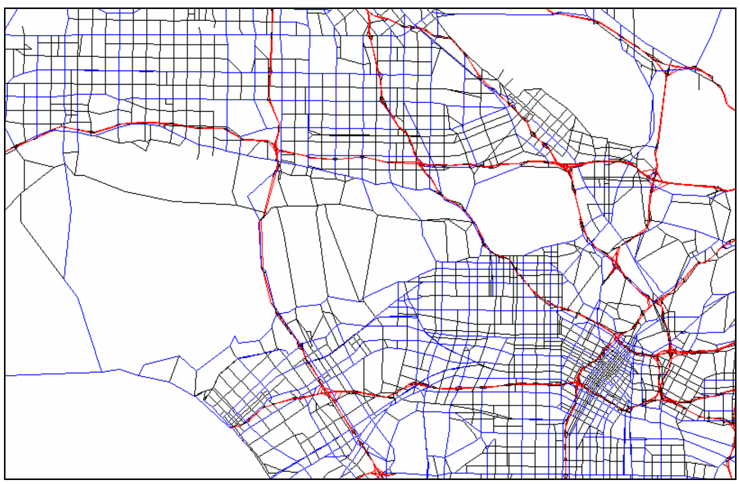
Table C-4 summarizes the size of each network, and Figure C-8 shows parts of each network. In particular, Figures C-8a, b, and c show the identical area of the network data used in this test.

Table C-4: Size of Networks used for Running-Time Comparison

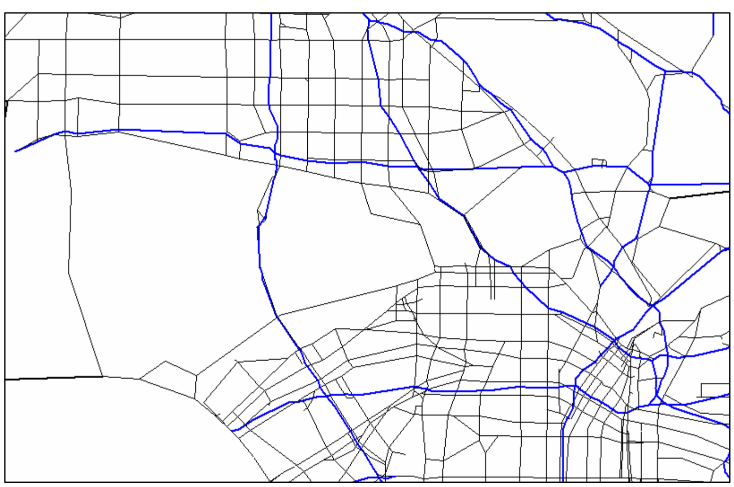
Network	Number of Zones	Number of Nodes	Number of Links
SCAG-1534	1,534	7,478	22,244
SCAG-3217	3,217	28,467	88,649
SCAG-1470	1,470	29,937	95,083
LA-480	480	1,970	6,230
Bay-1120	1,120	9,405	26,904



(a) SCAG-1534

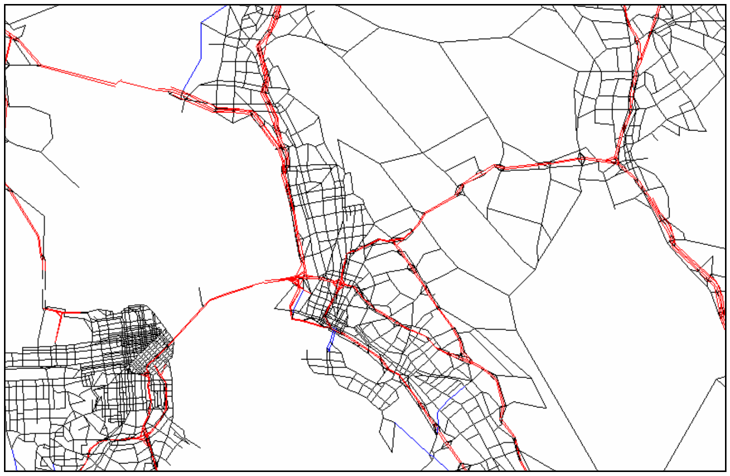


(b) SCAG-3217



(c) LA-480

Figure C-8. Network Data used for Comparison (Part 1 of 2)



(d) Bay-1120

Figure C-8. Network Data used for Comparison (Part 2 of 2)

Computation times for 30 all-to-all paths are compared. In the transportation network analysis, 15-to-30 extreme feasible solutions are used to improve the global solution (as explained above). This means that 15-to-30 sets of all-to-all paths are required. In the actual network analysis model, the paths keep changing according to the network configurations (and, in turn, the travel time). In this comparison, the algorithms are used to repeatedly establish the all-to-all path (30 different times).

Table C-5 demonstrates the efficiency of the dual-simplex algorithm. In all cases, the Dual-Simplex algorithm is faster than the Moore-Pape algorithm for the all-to-all minimum path search, by factors ranging from 24-percent to 57-percent.

As one might expect, the running time is closely related to the size of the network, as shown in Figure C-10. However, the efficiency of new algorithm seems to be related to the redundancy of the network, as indicated by the following examples:

- Since the SCAG-3217 and SCAG-1470 databases are very detailed, they provide more paths between zone-pairs. The Dual-Simplex algorithm does not need to examine all possible paths as does the Moore-Pape algorithm, the benefits from implementing the Dual-Simplex algorithm are high in this case (see Figure C-11).
- The Bay-1120 database contains very detailed network data but the configuration of this network is relatively simple. Only a few of the bridges cross over the San Francisco Bay, so the paths between some zone-pairs are limited. Therefore, the reductions in run time afforded by the Dual-Simplex algorithm relative to the Moore-Pape algorithm (about 28-percent) are not as great as for the SCAG databases.

Table C-5. Computer Run Times for Searching All-To-All Paths (30 times) by Networks and Algorithms (in seconds)

Network	Computer Run Time, seconds		Percent Reduction in Run Time when Dual-Simplex Algorithm is Used
	Moore-Pape Algorithm	Dual-Simplex Algorithm	
SCAG-1534	9.63	7.30	24.2 %
SCAG-3217	194.62	88.04	54.8 %
SCAG-1470	131.64	56.47	57.1 %
LA-480	0.69	0.53	24.0 %
Bay-1120	9.83	7.09	27.9 %

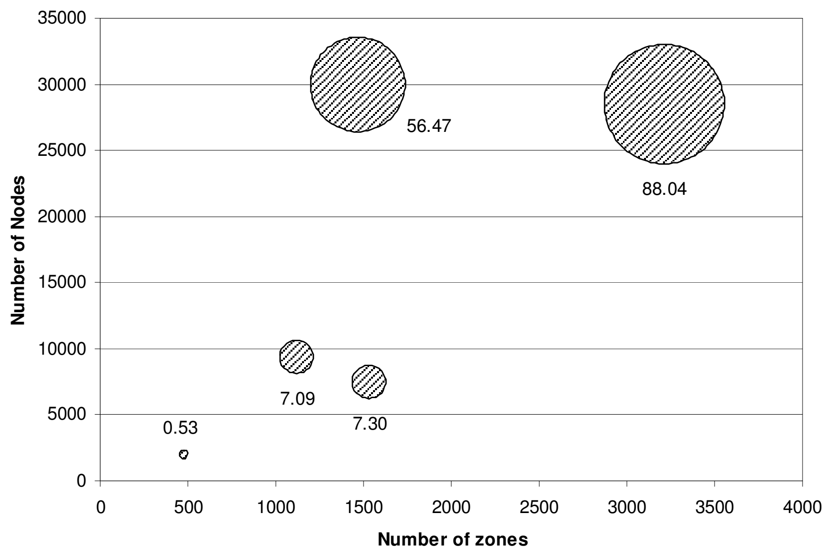


Figure C-9. Computer Run-Times of Dual-Simplex Algorithm as a Function of Network Size

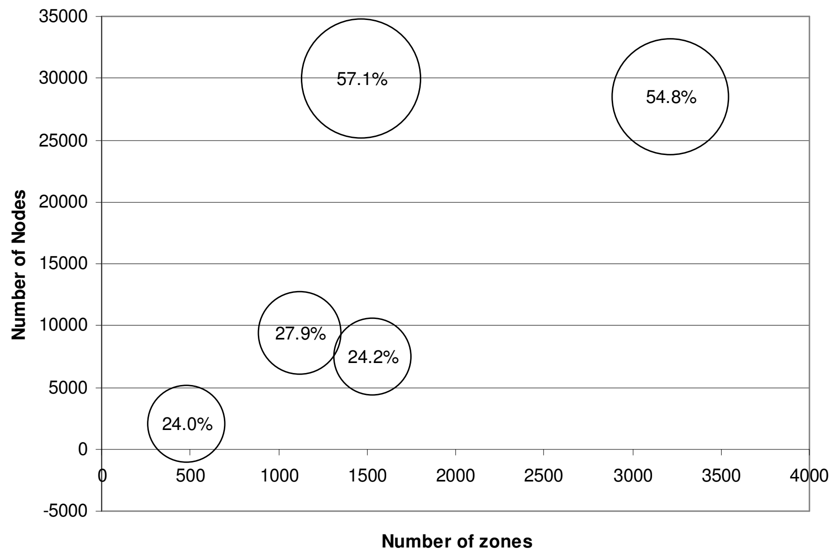


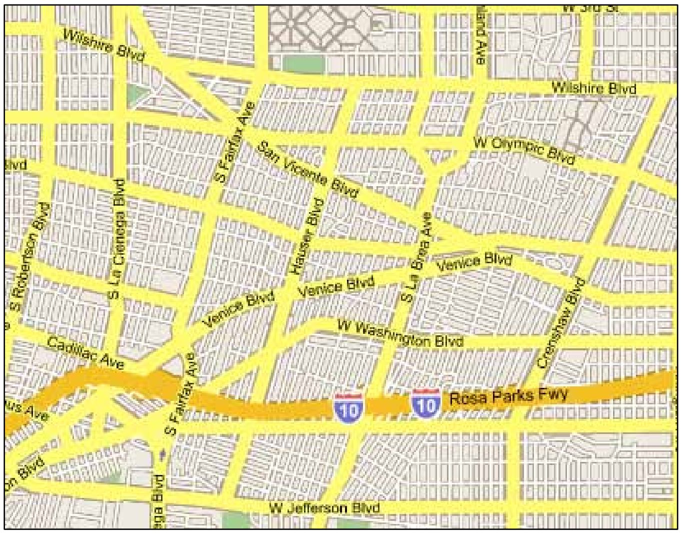
Figure C-10. Percent Reduction in Computer Run Time when Dual-Simplex Algorithm is Used, as a Function of Network Size

C.7 VALIDATION OF VARIABLE-DEMAND MODEL

In this section, the VDM is validated by comparing estimated traffic volume after the 1994 Northridge Earthquake to: (a) observed traffic volume after the earthquake; and (b) traffic volumes estimated by the fixed-demand user-equilibrium model that was implemented in prior versions of REDARS™. The section begins with a brief description of the data used in these comparisons. Then, these comparisons involving the VDM are presented in the form of a series of regression analysis results. Finally, overall economic losses due to Northridge-Earthquake-damage as obtained from the VDM results are compared to prior economic loss estimates by Caltrans.

C.7.1 Data used for Validation

According to the Northridge Earthquake Recovery Report (Caltrans,1995), traffic passing 10 locations was counted for 24 hours for the next day of the earthquake. In this validation, 1993 AADT data for the corresponding 10 locations is used for pre-earthquake traffic volume. Local traffic counts occurred for 12 hours on a day in October 1993 (exact date unknown) to represent pre-earthquake traffic volume, as well as on January 18, 1994, yielding the post-earthquake volume. These data covered 35 streets segments in the Los Angeles area bounded by Jefferson to the South, Wilshire to the North, Crenshaw to the East, and Robertson to the West. Figure C-11 shows the region where these street segments are located.



Source: maps.google.com

Figure C-11. Extent of Traffic Counts around I-10 / La Cienega Blvd. Intersection

Two sets of network data were created to estimate traffic volume corresponding to the Caltrans surveys: one network for freeways, and one network for local streets. A subset of the NHPN network was created for freeway traffic estimation, as well as the economic loss calculation, extending from I-105 to the south, just north of the I-5 /SR-14 intersection to the north, I-710 to the east, and the Ventura / LA county boarder to the west. This network consists of 1,036 TAZs, including 58 external zones. 3-hr daily average traffic demand was created from the 1996 SCAG planning OD. The Import Wizard was used to subset the OD into corresponding TAZs. Figure C-12 shows the resulting network.

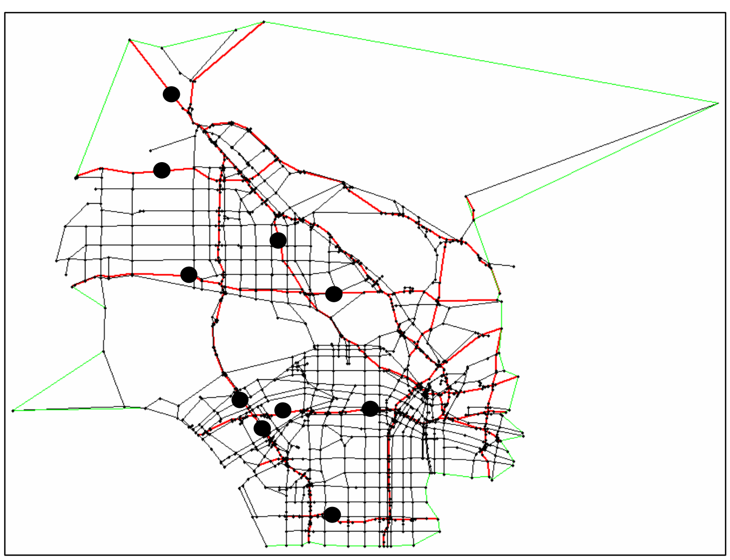


Figure C-12. The Regional REDARS™ Network used for Freeway Traffic Comparison (points are where volumes are counted)

Additionally, a detailed local network data was created to represent the local streets around I-10 / La Cienega Blvd, as shown in Figure C-11, based on 1996 SCAG planning network, and 2000 Tiger maps. This network data consists of 52 TAZs, including 31 external zones. Figure C-13 shows the resulting network. The demand-function coefficients are initially estimated using the demand-function calibration module, as described in Chapter 5.2.5, and implemented in the Import Wizard.

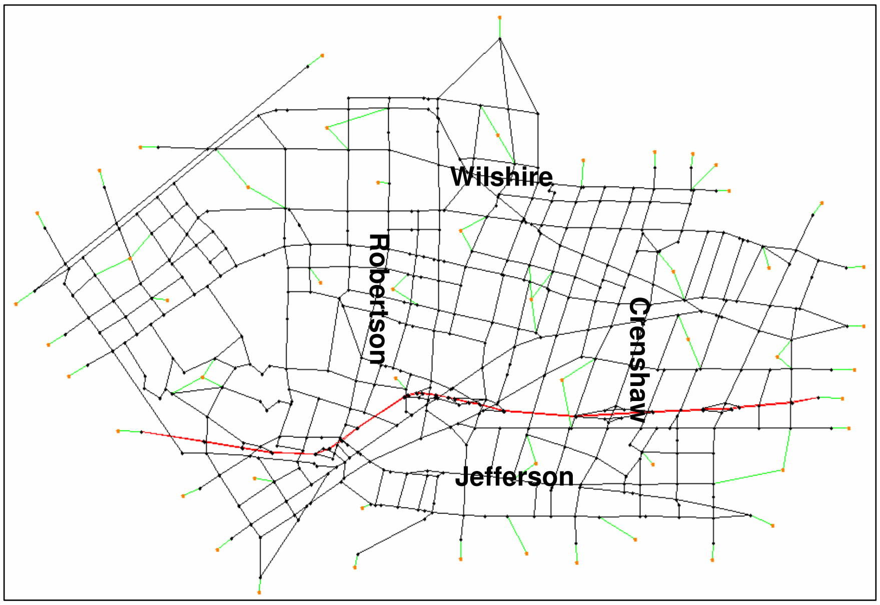


Figure C-13. The Regional REDARS™ Network used for local traffic comparison near I-10/La Cienega Blvd

C.7.2 <u>Traffic Volume Comparisons</u>

The traffic volumes in all the eight cases were analyzed by using the traffic modeling components of REDARS™ 2. As Table C-6 summarizes, the eight individual cases involve pre- and post-earthquake traffic volumes for both freeways and local streets, each analyzed using the fixed demand UE and VDM. The fixed demand UE model was temporarily programmed in the Import Wizard as a part of the baseline demand function calibration procedure; for purposes of this validation.

The volume estimated by the VDM is nearly always less than the volume estimated from the fixed demand UE model, in all of the cases listed in Table C-5, except for one data point that is explained below. In the VDM, trips and travel times are inversely related, so that any positive travel time increase will cause the trip demands to be reduced relative to the baseline (pre-earthquake) trip demands However, the fixed-demand UE, assumes that the post-earthquake trip demands are the same as the pre-earthquake demands, regardless of how the network's travel times and congestion are affected by earthquake damage. Because of this difference, the VDM traffic-volume estimates should not be greater than the volumes estimated by the fixed demand model.

Table C-5. Traffic Volumes Analyzed for Validation

Case No.	Network Configuration	Network Model	Network Data
1	Pre-Earthquake	VDM	Freeway
2	Pre-Earthquake	VDM	Local
3	Pre-Earthquake	Inelastic	Freeway
4	Pre-Earthquake	Inelastic	Local
5	Post-Earthquake	VDM	Freeway
6	Post-Earthquake	VDM	Local
7	Post-Earthquake	Inelastic	Freeway
8	Post-Earthquake	Inelastic	Local

In some case the VDM algorithm *as implemented* might not adjust trip demands relative to travel-time changes precisely as stated above.. For example, the VDM estimates a small positive volume on I-5, north of its interchange with SR-14. This is because of how the so-called "residual capacities" are handled in the VDM vs. how they are handled in the fixed-demand UE model. That is, to account for travel along smaller capacity roadways that are impractical to include into what is already a very large network model, REDARS™ 2 allows the user to account for this additional travel by specifying a residual traffic-carrying capacity for links that are disconnected. In this validation, 0.1% of each link's pre-earthquake capacity was used as the link's residual capacity when it is disconnected.

When the fixed-demand UE model is used, this small residual capacity results in extremely long travel times, because this incremental capacity increase tends to overload what may be an already near-capacity highway; i.e., because of this, the model shows that there no traffic volume is estimated north of I-5. By comparison, the VDM allocates some traffic to the link initially, because when the model starts analyzing the network, as demonstrated in Appendix C.5.2, the algorithm assumes that there is no volume on any of the links at the first iteration. The residual capacity does not effect the free-flow travel time on I-5. In subsequent iterations, although the traffic is getting smaller on the link as the algorithm of VDM proceeds, the algorithm actually does not reduce the volume to zero within a practical number of iterations. Despite this idiosyncrasy, using the residual capacity option is more appropriate for the VDM than for the fixed demand UE version, since the VDM maintains a small amount of traffic on links with minimal residual capacity.

The regression analysis reveals strong linear relationships between observed and estimated data from both the fixed-demand UE model, and the VDM. The statistics from the simple regressions summarized in Table C-6 indicate highly significant results for F-statistics, the confidence level, and a meaningful *t*-statistic on the estimated slope (β). There is no significant difference in the fit of the two models, since their calculated r^2 values have similar ranges when compared to the estimated traffic volumes. However, with regard to the pre-and-post-volume ratio, r^2 based on VDM estimations are much higher than for the fixed-demand UE model. Figures C-14 and C-15 show the data used for the series of regression analyses.

Because the difference between pre and post earthquake conditions is the basis for analyzing losses, traffic volumes estimated under pre earthquake conditions is as important as the volumes under post-earthquake conditions. As Figure C-16 shows, the actual increment of post-earthquake traffic volume was observed by Caltrans to be as much as twice the pre-earthquake link volume. Note that the post-earthquake network configuration includes the closed bridges on I-10, and only the local streets are used to accommodate the travel demand. Even though the VDM reduces the number of trips, the remaining trips increase link traffic volume. The VDM estimates a similar change ratio of 2.1 whereas the fixed demand UE model results in as much as 5.7 times the post-earthquake volumes on local streets. This simple test shows that the VDM adequately maintains the traffic volumes on pre and post earthquake network configurations.

In closing, the above results show that the VDM is a more appropriate for SRA than fixed demand model because of the manner in which residual traffic is accounted for when modeling detours, and the pre- to post earthquake traffic volume change ratio.

Table C-6. Regression Statistics for the VDM and Fixed Demand UE model

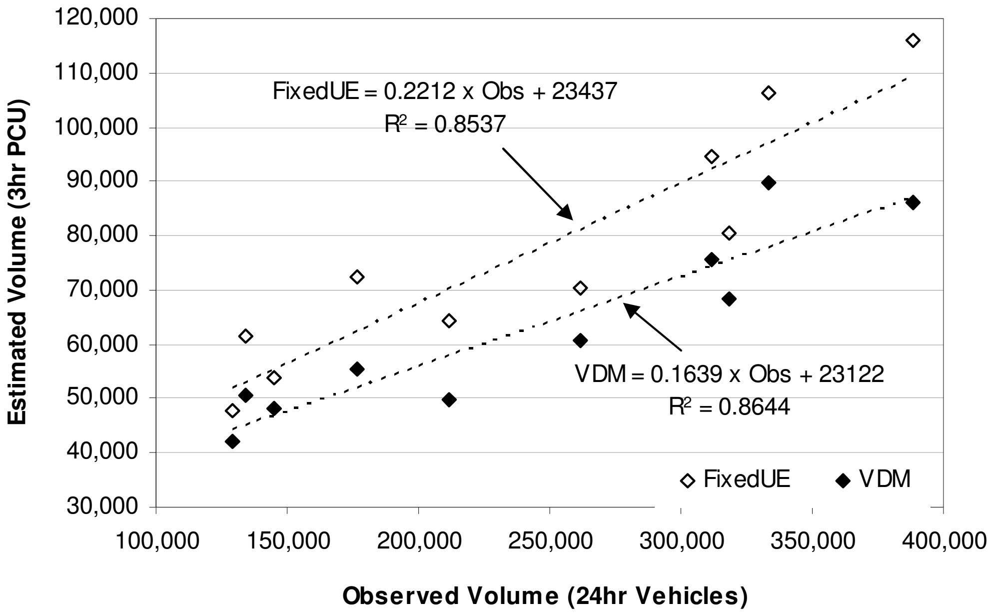
a) Traffic Volume on Freeways

Dependent Variable	α	β	r^2	F
Pre-Earthquake, Fixed Demand	23437.2 (t=2.816, p=0.023)	0.2212 (t=6.832, p=0.000)	0.8537	46.671 (p=0.000)
Pre-Earthquake, VDM	23122.4 (t=3.921, p=0.004)	0.1639 (t=7.142, p=0.000)	0.8644	51.010 (p=0.000)
Post-Earthquake, Fixed Demand	23608.3 (t=2.781, p =0.024)	0.2726 (t=6.255, p=0.000)	0.8303	39.128 (p=0.000)
Post-Earthquake, VDM	14299.5 (t=2.425, p=0.042)	0.2126 (t=7.024, p=0.000)	0.8605	49.337 (p=0.000)
Change Ratio, Fixed Demand	0.3468 (t=2.869, p=0.021)	0.7875 (t=4.876, p=0.001)	0.7483	23.779 (p=0.001)
Change Ratio, VDM	0.2453 (t=3.381, p=0.010)	0.7893 (t=8.143, p=0.000)	0.8923	66.311 (p=0.000)

b) On Local Street near I-10 / La Cienega Blvd.

Dependent Variable	α	β	r^2	F
Pre-Earthquake, Fixed Demand	-7162.5 (t=-0.971, p=0.338)	2.5869 (t=9.234, p=0.000)	0.7149	85.274 (p=0.000)
Pre-Earthquake, VDM	-1775.6 (t=-1.046, p=0.303)	0.6252 (t=9.695, p=0.000)	0.7344	93.991 (p=0.000)
Post-Earthquake, Fixed Demand	11161.1 (t=0.646, p=0.523)	3.6831 (t=5.667, p=0.000)	0.4858	32.119 (p=0.000)
Post-Earthquake, VDM	-2346.8 (t=-1.032, p=0.310)	0.6484 (t=7.584, p=0.000)	0.6484	57.522 (p=0.000)
Change Ratio, Fixed Demand	-1.5888 (t=-4.332, p=0.000)	3.4309 (t=10.124, p=0.00)	0.7509	102.503 (p=0.000)
Change Ratio, VDM	-0.1464 (t=-1.561, p=0.128)	1.1344 (t=13.088, p=0.00)	0.8344	171.309 (p=0.000)

a) Pre-earthquake Volume



(b) Post-earthquake Volume

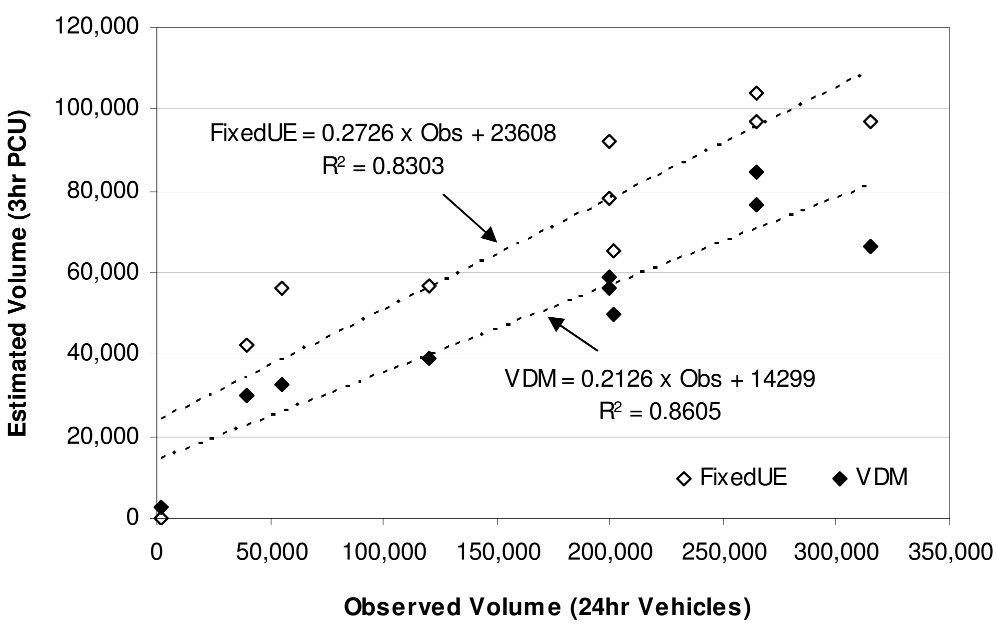
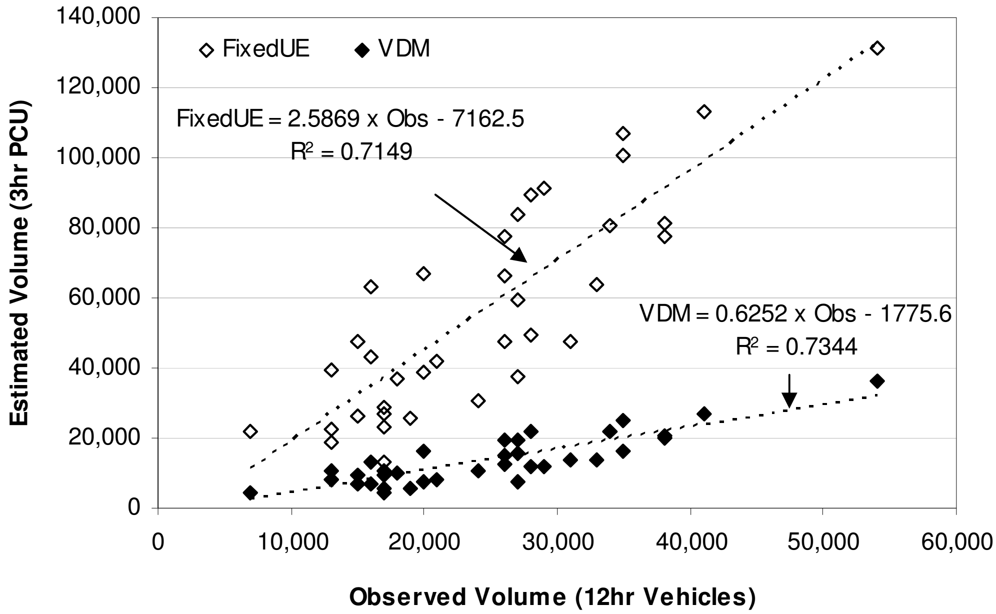


Figure C-14. Pre and Post-Earthquake Freeway Traffic Volume

(a) Pre-earthquake Volume



(b) Post-earthquake Volume

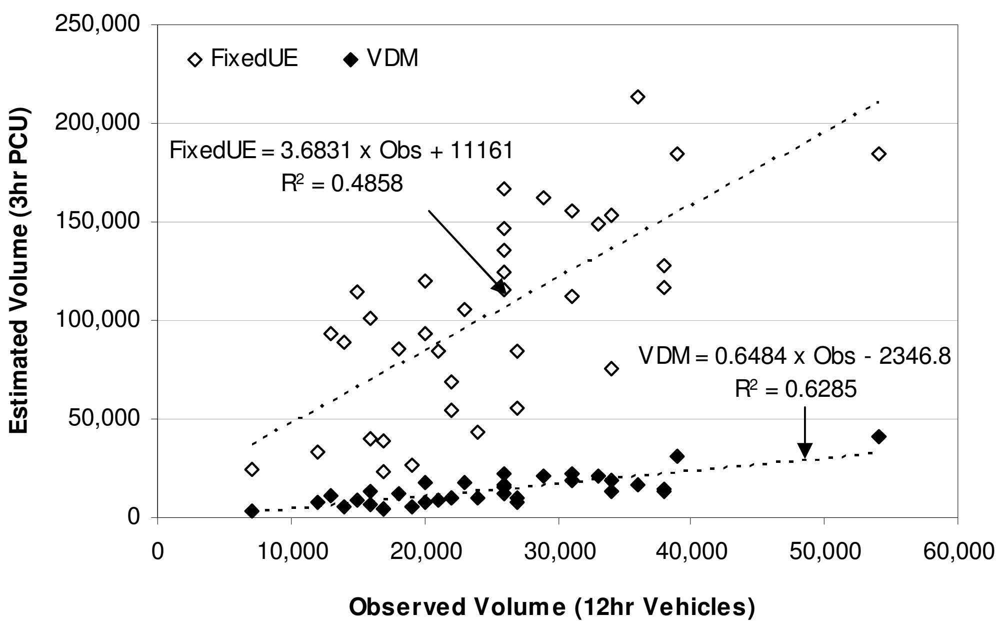
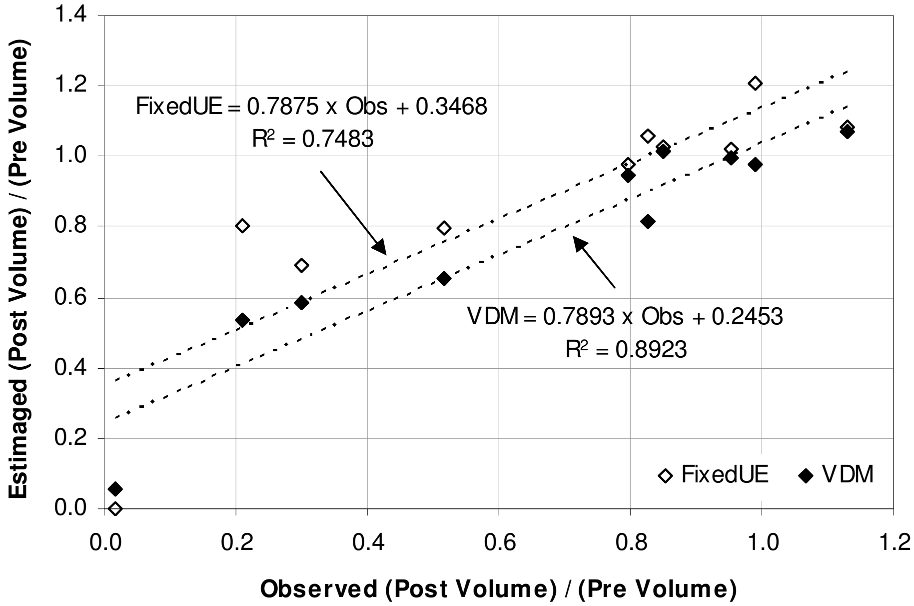


Figure C-15. Pre and Post-earthquake Local Traffic Volume

(a) Volume Changes on Freeway due to the earthquake



(b) Volume Changes on Local Streets due to the earthquake

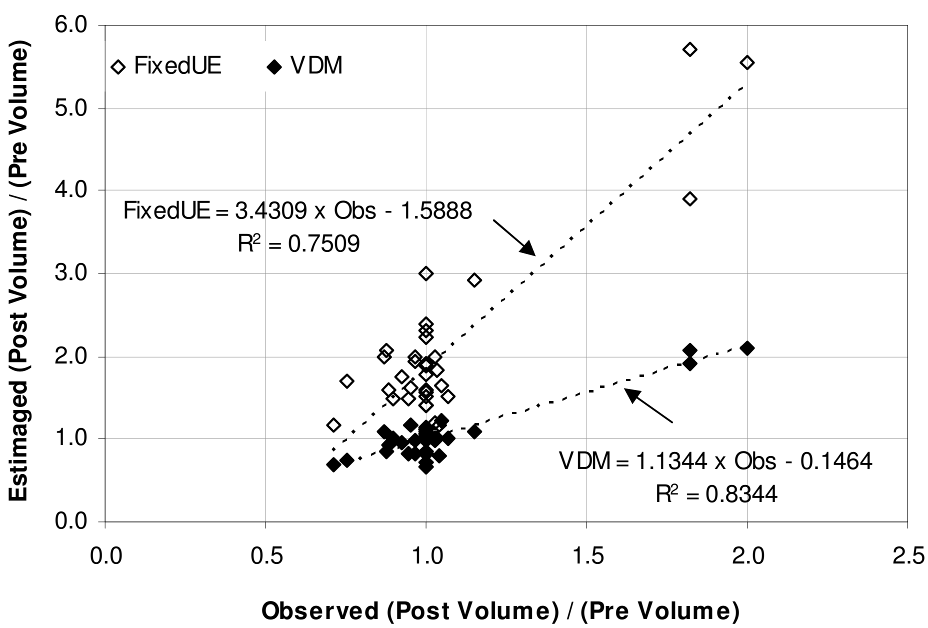


Figure C-16. Post earthquake Volume Ratio to Pre earthquake

C.7.3: Economic Loss Estimation

Caltrans estimates a $217 million loss from transportation disruption near collapsed bridges following the Northridge earthquake. Table C-7 presents the economic loss estimated using REDARS™ 2, the result is very comparable at $213million.

Table C-7. Economic Losses Estimated Using REDARS™ 2

Days [3] from EQ.	Passenger [1]		Freight [2]		Daily Loss ($ 1,000)	Total Loss over the days ($1,000)
	Forgone Trips (PCU*Hr)	Congestion (PCU*Hr)	Forgone Trips (PCU*Hr)	Congestion (PCU*Hr)		
11	1,460	78,650	301	5,875	2,661	29,268
12	1,373	76,887	299	5,666	2,593	2,627
15	1,244	69,609	276	5,131	2,348	7,413
81	375	25,745	242	1,723	863	105,989
123	89	23,034	8	920	695	32,726
174	72	10,470	1	642	336	26,283
228	0	0	0	0	0	9,062
					Sum	213,367

1) $6 / PCU·Hr to convert daily loss
2) $19.2 / PCU·Hr to convert daily loss
3) Recovery schedule from Northridge Earthquake Recovery Report – Final Comprehensive Transportation Analysis, Caltrans District 7, 1995.

Note that this promising economic loss estimation is obtained by using only the transportation model in REDARS™ 2 outside of the standard software package. In this calculation, the networks are analyzed for 7 time periods, while REDARS™ 2 can accept 4 time periods after earthquake. Furthermore, the system states at each time period were entered, instead using REDARS™ to estimate.

Although the difference is small, it is less than the Caltrans estimation. For a deterministic analysis, the model may not be conservative, as is required for planning models. This may be related to the low estimation of pre-earthquake traffic volume. The validation found VDM volumes are consistently lower than the fixed demand model, even in the pre-earthquake conditions. This is by design, the input OD is used by the VDM as an upper bound for demand which is reduced according to travel time. Since the MPO OD was developed for normal network conditions, any network model should use all of the OD without any reduction for pre-earthquake condition. Once the pre-earthquake trips are estimated, the VDM further reduces trips to adjust for post-earthquake network capacity. Further improvement of the VDM should address the elasticity of pre-earthquake demand.

APPENDIX D
DEMONSTRATION APPLICATION

D.1 OBJECTIVE AND SCOPE

This appendix, which is extracted from Werner et al. (2006), describes a demonstration application of the REDARS™ 2 software to a highway-roadway system that extends through the northern, western, and central sections of the greater Los Angeles (LA), California area, and is hereafter referred to as the LA-testbed highway-roadway system (see Section D.2). This analysis shows how REDARS™ 2 can be applied to a major roadway system and, in addition, illustrates how REDARS™ 2 can be used to guide seismic-risk-reduction decision-making by estimating how various risk-reduction-options affect losses due to traffic-flow and travel-time disruptions.

The demonstration SRA consists of three applications of REDARS™ 2 to this 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 (Sec. 4.2). The first part, which is described in Section D.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 hazards throughout the roadway 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 traffic flows and travel times; and (d) losses due to any traffic flow and travel time disruptions that may occur. As noted earlier in this manual, 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 post-earthquake recovery of the region.

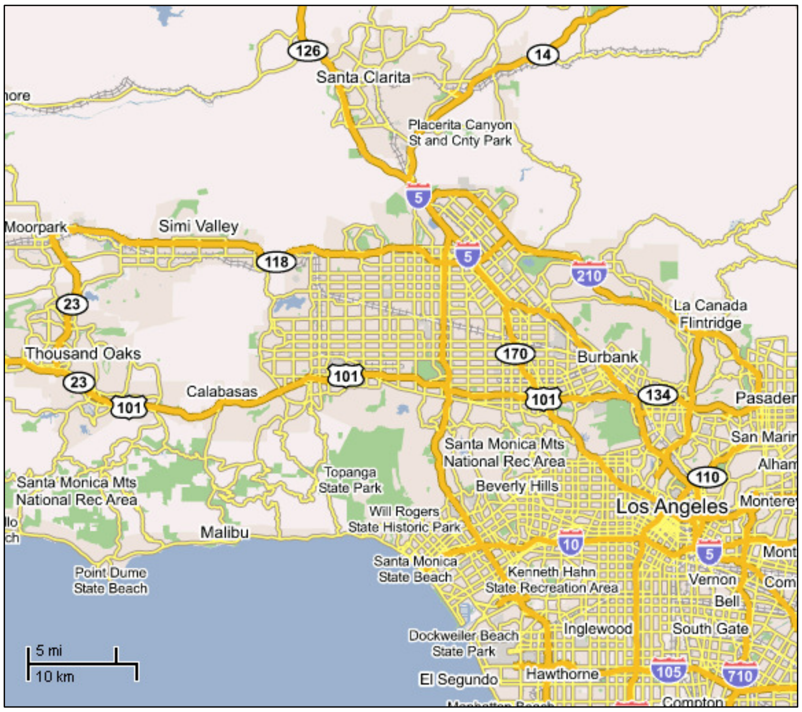
The remaining applications of REDARS™ 2 are probabilistic. The first of these applications, which is described in Section D.4, is based on the same highway system and component attributes as considered in the deterministic analysis and provides the same types of results. However, now, the analysis accounts for how these results are affected by uncertainties in earthquake occurrence and in the estimation of seismic hazards and component damage states. As summarized in Chapter 2, this involves the development of multiple simulations for multiple scenario earthquakes listed in the Coastal California walkthrough table.

The last application (Section D.5) involves use of REDARS™ 2 results in an example assessment of 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 uncertainty in the losses is reduced by these additional retrofits.

D.2 MODELS

D.2.1 Highway-Roadway Network

Figure D-1 shows the LA-testbed highway-roadway 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 D-1. LA-Testbed Highway-Roadway System

The REDARS™ 2 model of this system (Fig. D-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).

D.2.2 Bridges

This roadway system contains 944 bridges, of which 288 have been retrofitted by column jacketing (see Fig. D-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 unretrofitted-bridge capacities by damage-state-dependent enhancement factors that were developed by Shinozuka (2004).

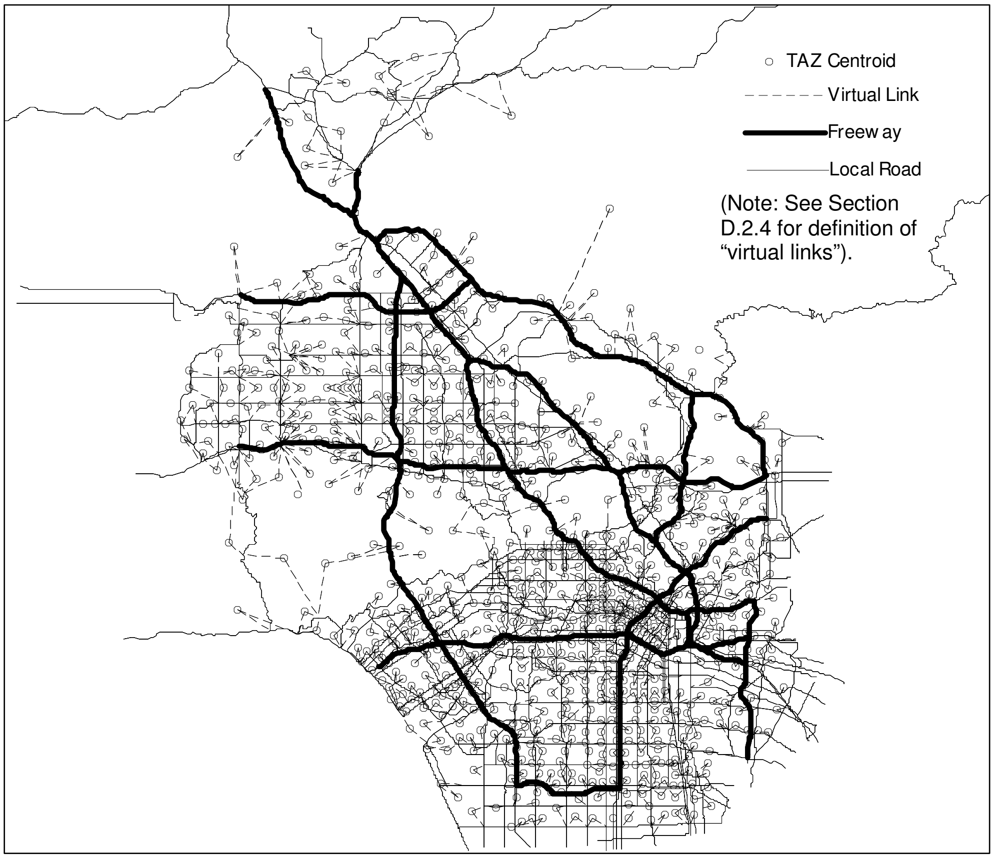


Figure D-2. REDARS™ 2 Model of LA-Testbed Highway-Roadway System

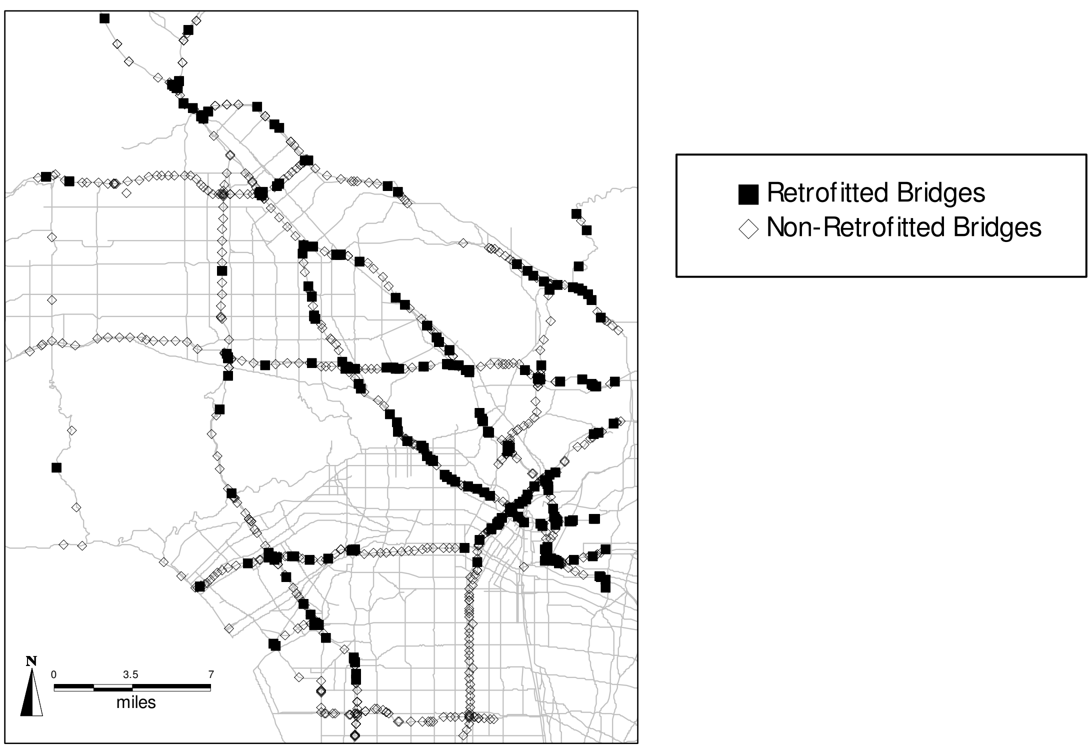


Figure D-3. Locations of Bridges in LA-Testbed Highway-Roadway System

D.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. D-4). None of the soils within the system are considered to be prone to liquefaction hazards.

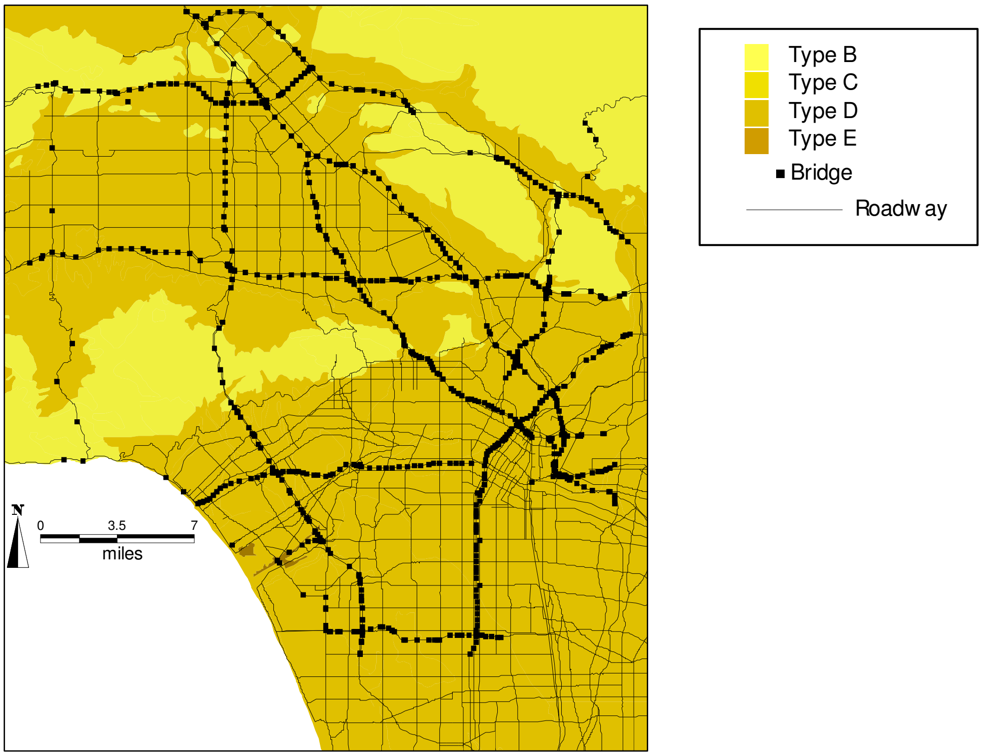


Figure D-4. Soil Conditions (in terms of NEHRP Site Classifications) Throughout LA-Testbed Highway-Roadway System

D.2.4 Traffic Analysis Zones

Figure D-5 shows the section of the greater LA area within which this highway-roadway 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-roadway system (see Fig. D-2).

Several of these TAZs are highlighted in Figure D-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.

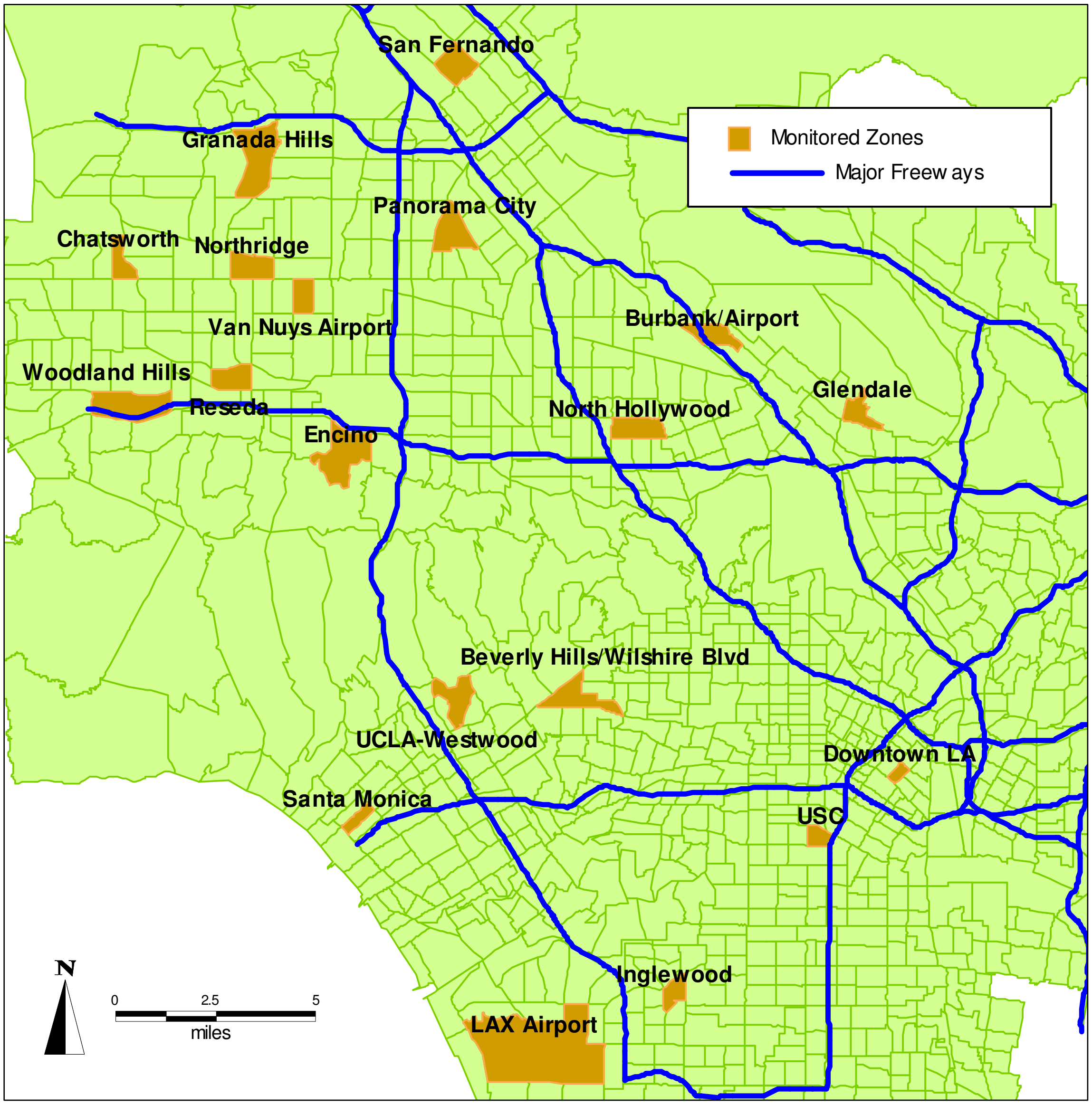
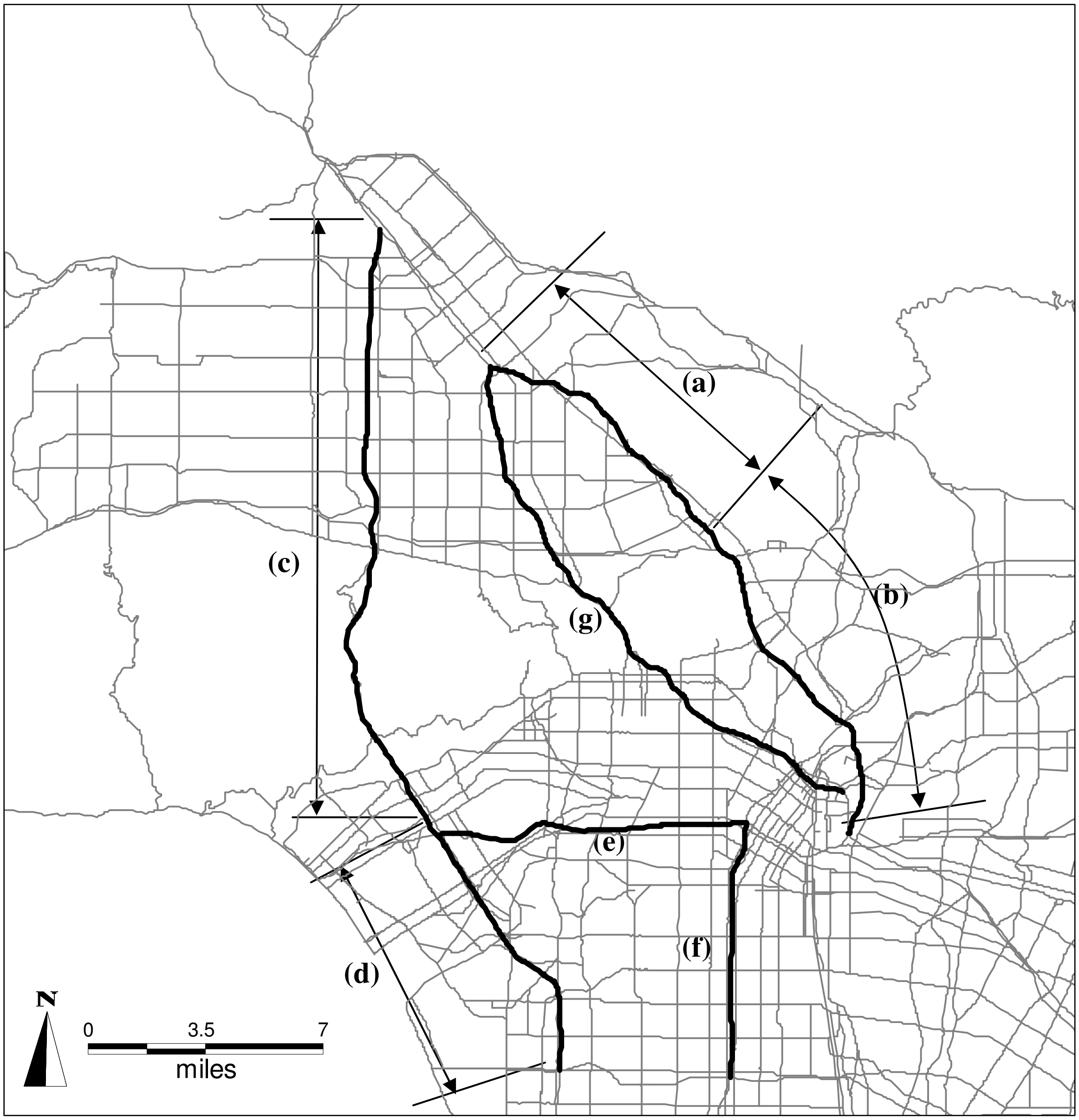


Figure D-5. Traffic Analysis Zones whose Travel-Tmes and Trips to/from These Zones are Displayed as Output from this Demonstration Application

D.2.5 Routes

Figure D-6 shows selected routes within this LA-testbed highway-roadway 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 D-6. Routes whose Travel Times are Displayed as Output from This Demonstration Analysis

D.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-roadway system. They consist of 7,035 earthquakes with $M_w \geq 5.0$, whose breakdown by moment magnitude is shown in Figure D-7. Of these, it turns out that 2,645 of these events actually damaged this system (see Sec. 2.4.1.4 of Chap. 2). Only these damaging events were considered in the probabilistic SRAs described in Sections D.4 and D.5.

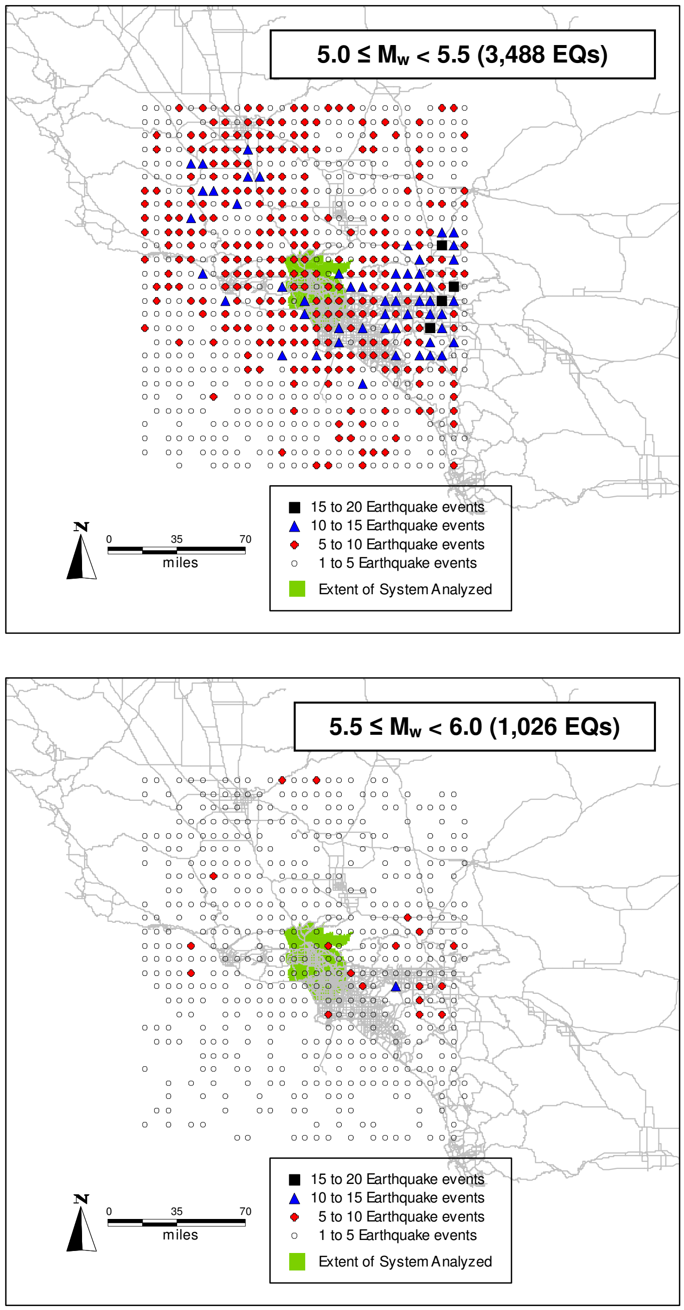
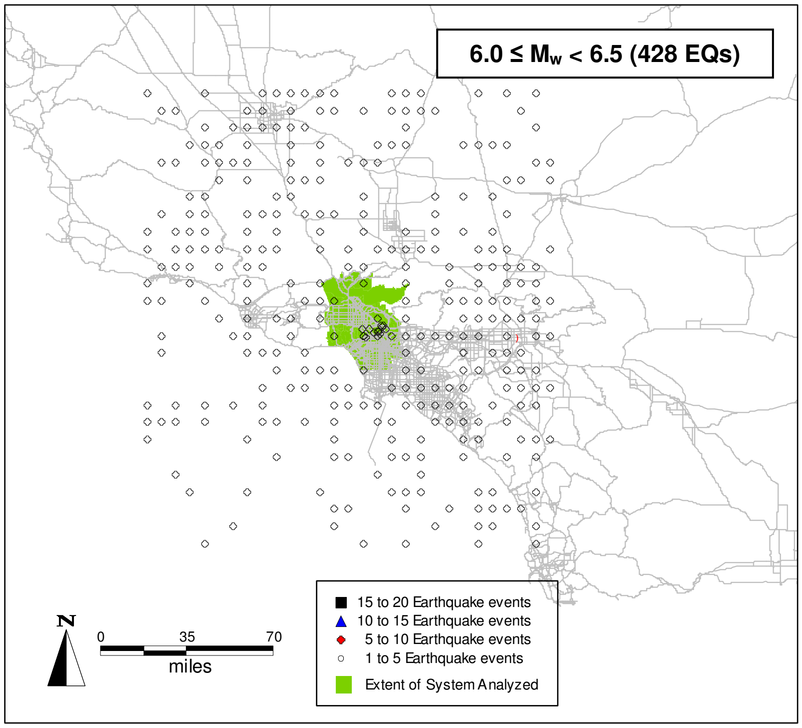


Figure D-7. Epicenters of Earthquake Scenarios in 10,000-Year Walkthrough Table



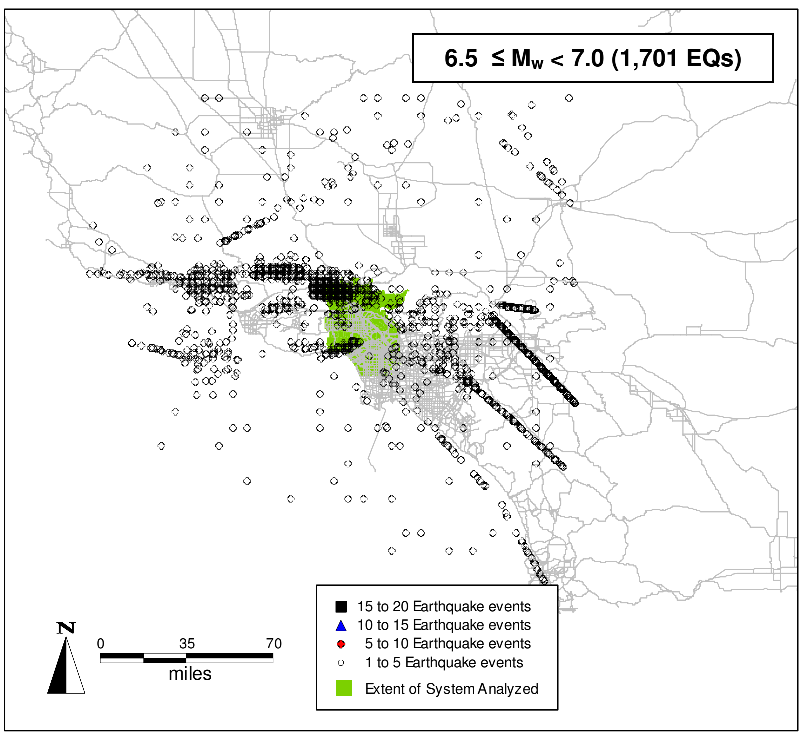
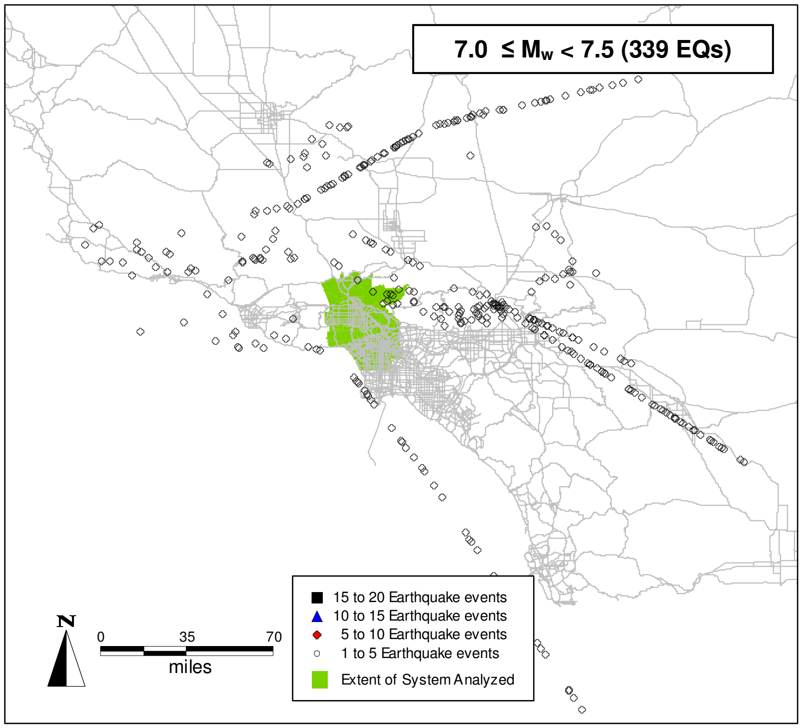


Figure D-7. Epicenters of Earthquake Scenarios in 10,000-Year Walkthrough Table (continued)



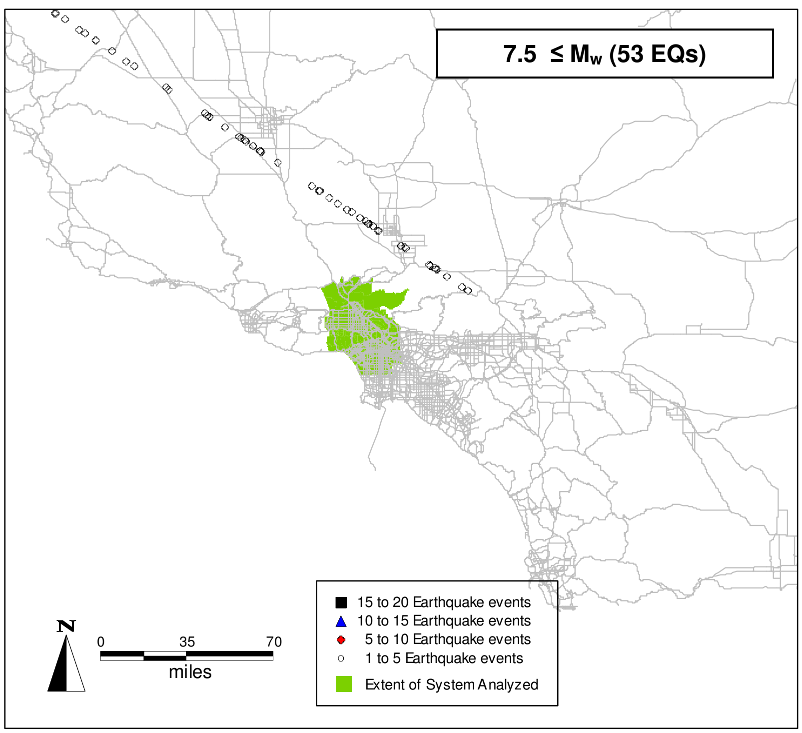


Figure D-7. Epicenters of Earthquake Scenarios in 10,000-Year Walkthrough Table (concluded)

D.3 DETERMINISTIC ANALYSIS

The first part of this demonstration application consists of a deterministic analysis of the seismic performance of the LA-testbed highway-roadway 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.

D.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. D.4 and D.5). The epicenter of this earthquake is located within the Pacific-Pallisades/Santa-Monica area, about 2.5 km inland from the Pacific-Ocean coastline (e.g., Fig. D-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[1]. 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. D-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.

D.3.2 Seismic Hazards

D.3.2.1 Ground Shaking

Figure D-8 shows the distribution and intensity of ground motions throughout this highway-roadway system that are caused by this earthquake scenario. The ground motion results are provided here as spectral accelerations at a period of 1.0 sec., since this is the ground-motion parameter that will be considered for most of the bridges by the REDARS™ 2 default model for estimating bridge damage due to ground shaking (see Sec. 5.3). 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 0.6g - 0.8 g) also occurs along some segments of I-10 that are west of I-405.

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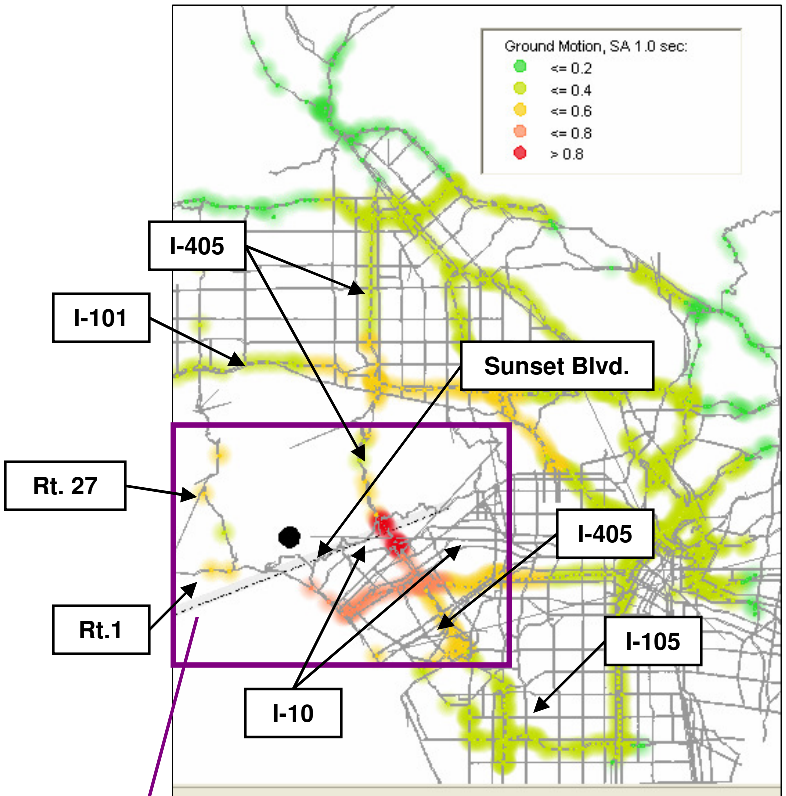
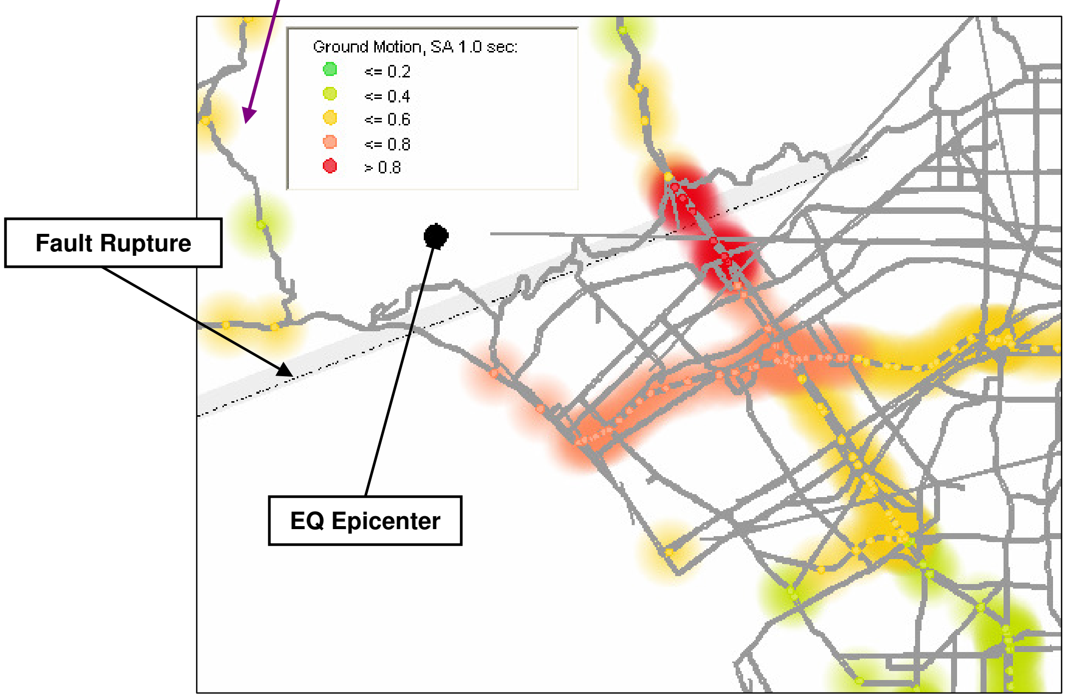
[1] As noted in Appendix B of Werner et al. (2006), The lengths and widths of the fault rupture for each earthquake scenario are estimated from Wells and Coppersmith (1994), including uncertainties. Uniform random variates are used to estimate the location of the epicenter within the projection of the fault plane onto the ground surface.



a) System-Wide Ground Motions



b) Area with Most Severe Ground Motion

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

D.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 D-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 D-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 this testbed roadway system are much more consistent with intuition.

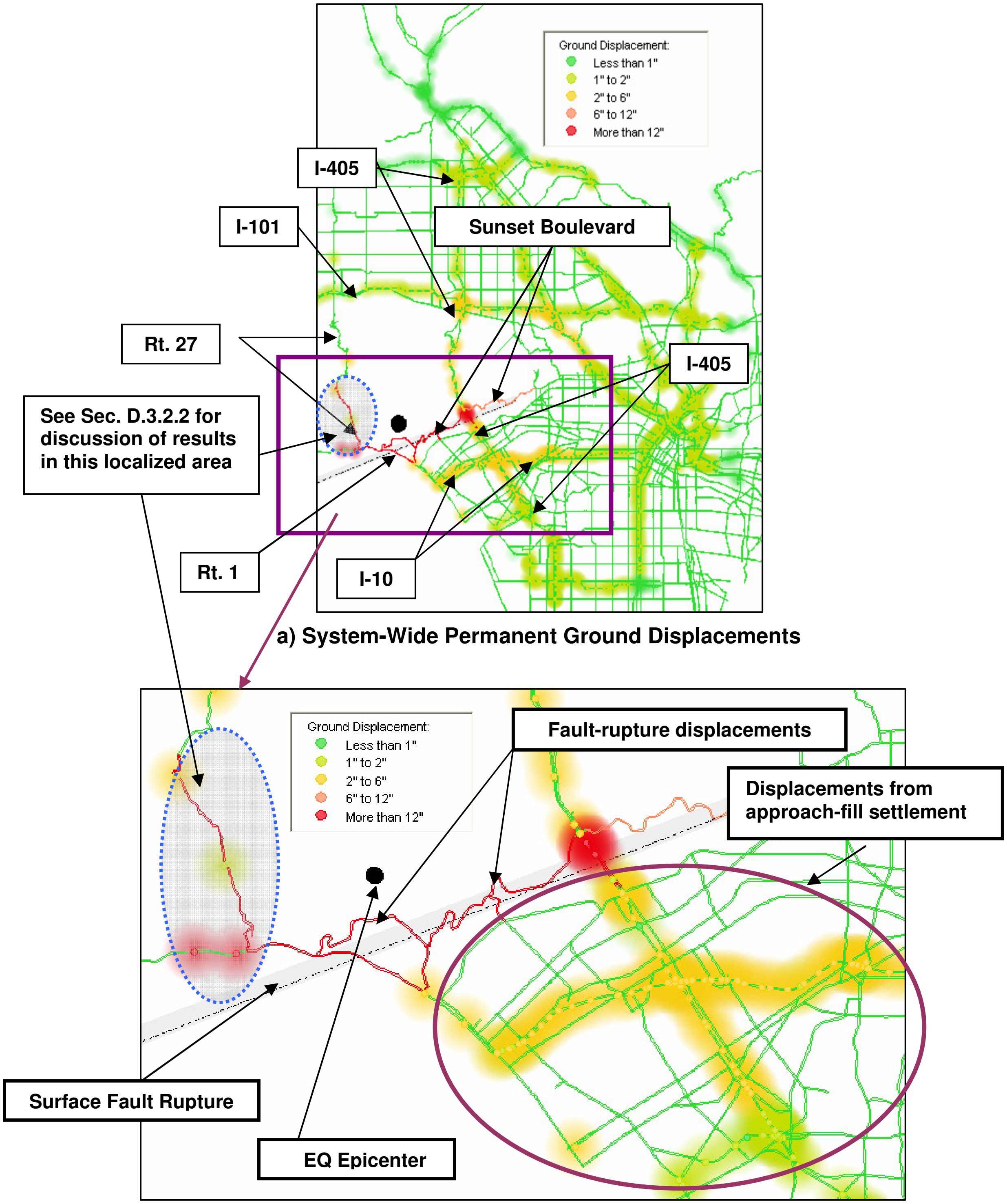
D.3.2.3 Approach Fill Settlement

Figure D-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.

D.3.3 <u>Component Performance</u>

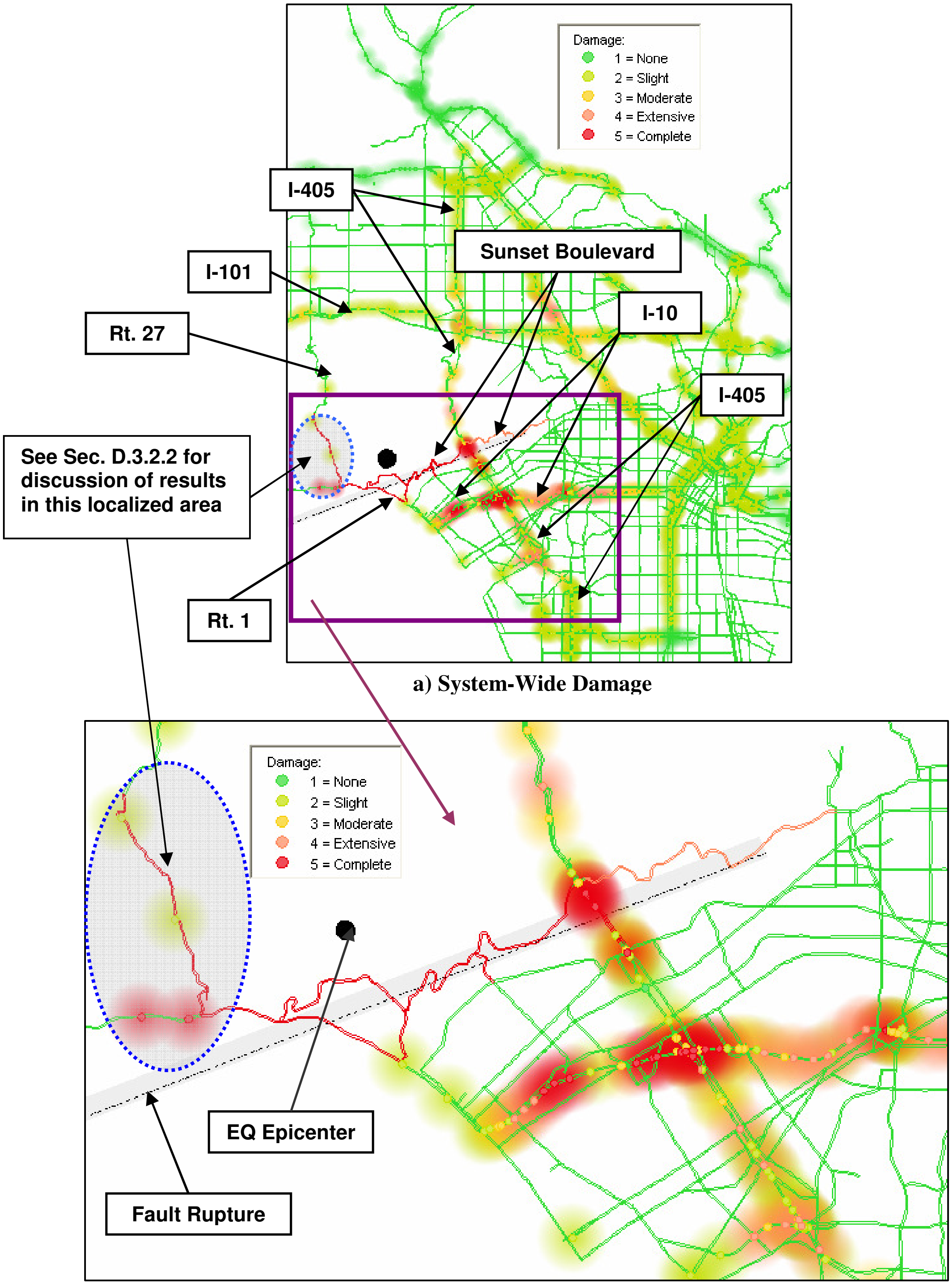
The seismic performance of the various components is this highway system is summarized in Table D-1. This table shows that 20 of the 944 bridges in the system are estimated to suffer complete damage (i.e., collapse) and 31 additional bridges are estimated to experience extensive damage. The table also 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 D-10 provides a map of the LA-testbed highway-roadway 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.



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

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



a) System-Wide Damage

b) Area with Greatest Damage to Components

Figure D-10. Component Damage States

Table D-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

Reasons for this large number of bridge collapses become clear from data provided in Table D-2. This table lists seismic-design, seismic-retrofit, and structural-attribute data for the 20 collapsed bridges and 5 nearby bridges that did not collapse, as well as each bridge's seismic hazards and damage state due to this earthquake. The following trends are noted from this list:

- Five of the bridges (those highlighted with light blue shaking in Table D-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, which is where the fault rupture crosses I-405. The two remaining collapsed bridges are located along a segment of Route 1 just west of Route 27, and are attributed to the fault-displacement issues discussed in Section D.3.2.2.
- The remaining 15 bridges (highlighted with light grey shading in Table D-2) are estimated to have collapsed due to strong ground shaking. Table D-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 D-2 lists five of the bridges that are immediately adjacent to the above 15 collapsed bridges but did not themselves collapse. Two of these bridges (which are numbered 231 and 264 in Table D-2 and are highlighted with rose 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 D-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 (Chap. 5). 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 D-2. Collapsed Bridges and Nearby Un-Collapsed 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.

D.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-roadway systems in other parts of the country, where experience levels, construction practices, and repair resources will usually differ from those of Caltrans.

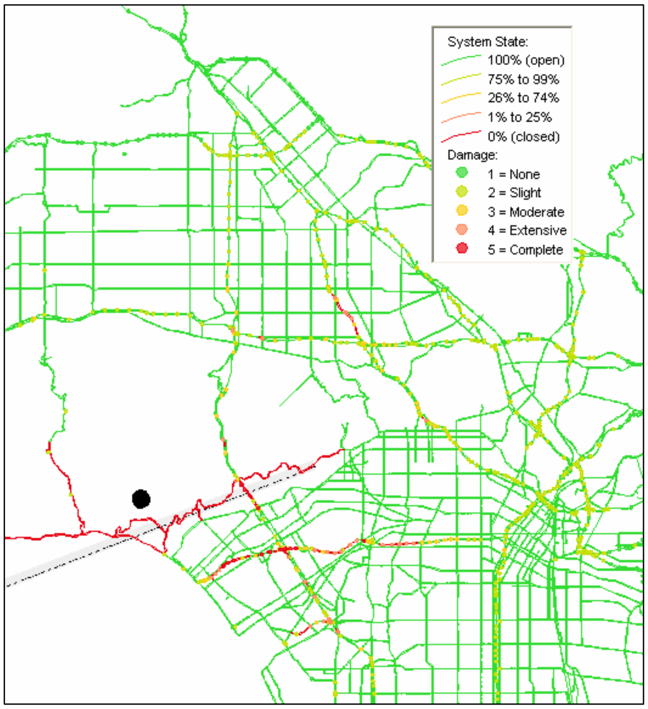
For the levels and types of component damage summarized in Section D.3.3, these repair models result in the estimated system states shown in Figure D-11 for four different times after the earthquake (7-, 60-, 150-, and 221-days). In this assessment, the post-earthquake time of 7 days was chosen to typify 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. Based on the default component repair models described in Appendices G and H, this is assumed to be the time after the earthquake when all repairs are fully completed and the highway-roadway system first returns to its pre-earthquake condition. The post-earthquake times of 60 days and 150 days are intended represent intermediate times after initiation of the system repairs and before the repairs are completed throughout the system.

Therefore, the system state for 7 days after the earthquake contains closed links that reflect the locations of the more severely damaged components. Accordingly, for this particular analysis, Figure D-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.

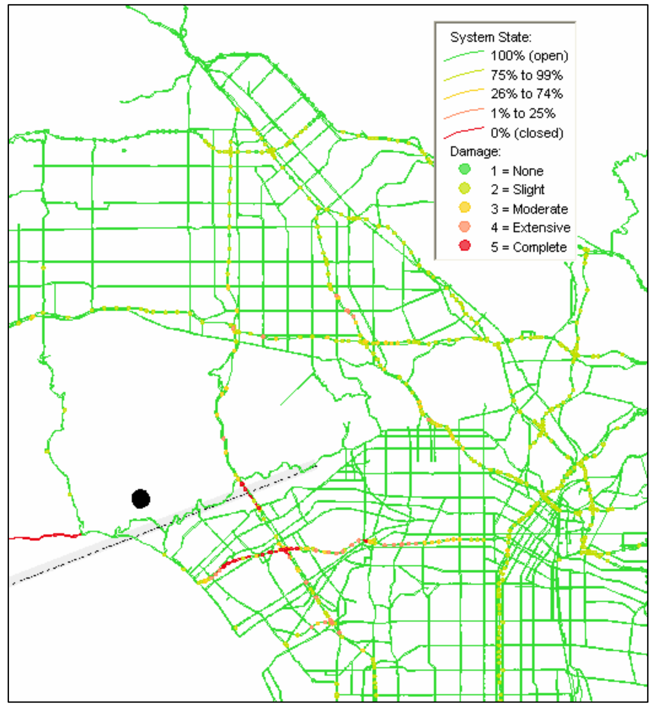
At subsequent days, Figure D-11 shows that the number of closed links decreases as the repairs proceed in accordance with the REDARS™ component-repair models. These system states at successively increasing intermediate post-earthquake times will tend to converge with increasing time toward the fully-open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

D.3.5 Traffic and Trip-Demand Impacts

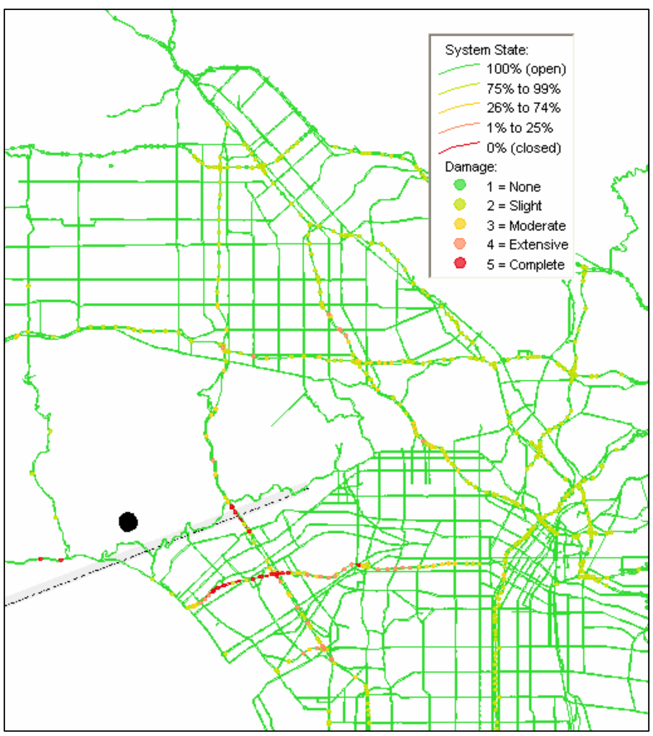
The next step in this deterministic analysis of this highway-roadway system consisted of application of the network analysis models described in Chapter 5 and Appendix I to each of the system states shown in Figure D-11. These models estimate how earthquake-induced roadway system damage and associated congestions affect post-earthquake travel times, traffic impacts, and trip demands on the system (see Chap. 5 and App. I).



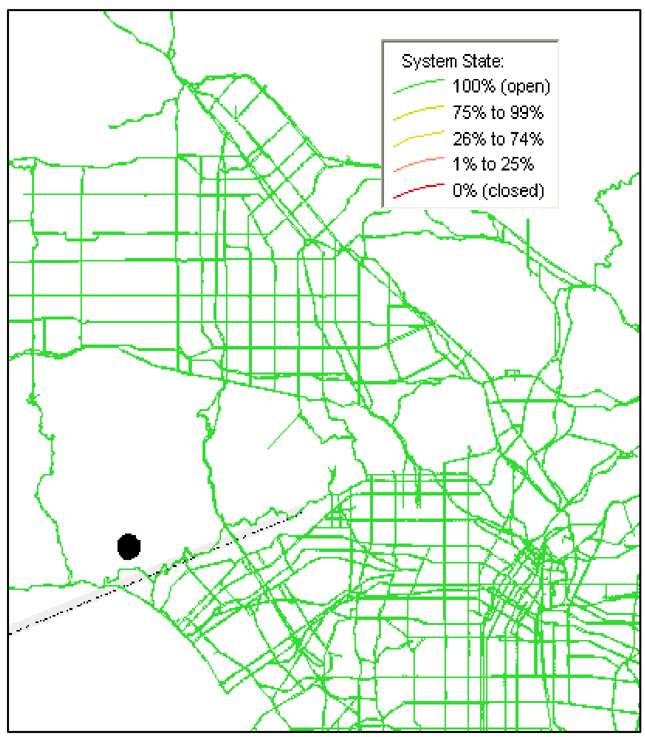
a) 7 Days after Earthquake



b) 60 Days after Earthquake



c) 150 Days after Earthquake



d) 221 Days after Earthquake

Figure D-11. Post-Earthquake System States

Table D-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 system, and that the trip demands on the system is reduced by about 8-percent. Table D-3 also shows how these traffic impacts decrease over time after the earthquake, as the repairs to the damaged components proceed.

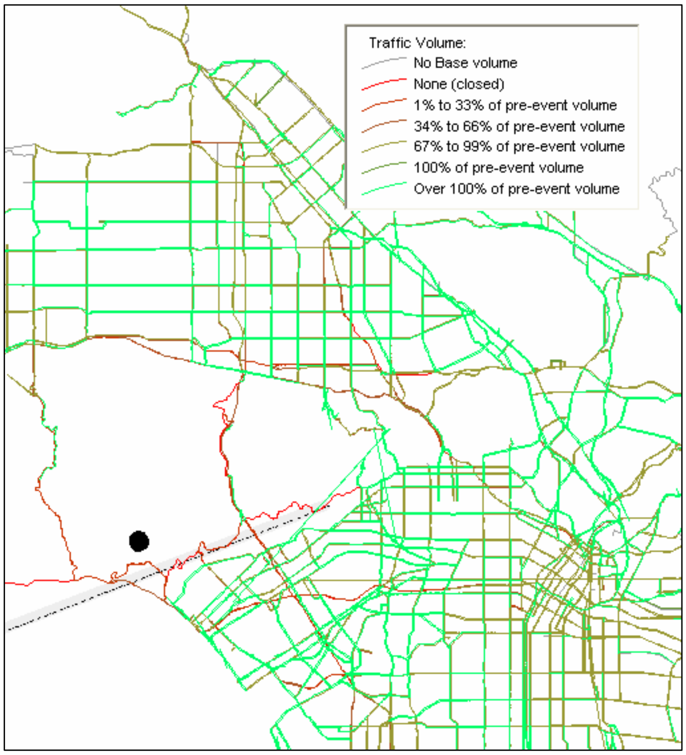
Table D-3. Summary of Estimated Earthquake Impacts on System-Wide Traffic

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%

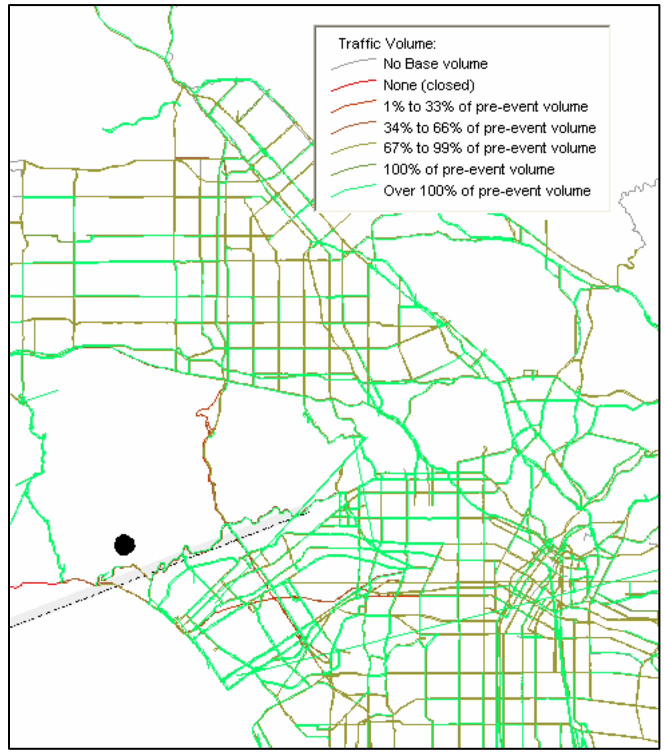
REDARS™ 2 provides several types of graphical system-wide maps and tabular data to show various traffic impacts from earthquake damage to the highway-roadway system. Graphical system-wide maps provided by REDARS™ 2 for this purpose are summarized below:

- ***System-Wide Post-Earthquake Traffic Volumes (Fig. D-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, these I-405 and I-10 freeway segments remain closed, but other previously-closed links 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 an estimated time 221 days after the earthquake.

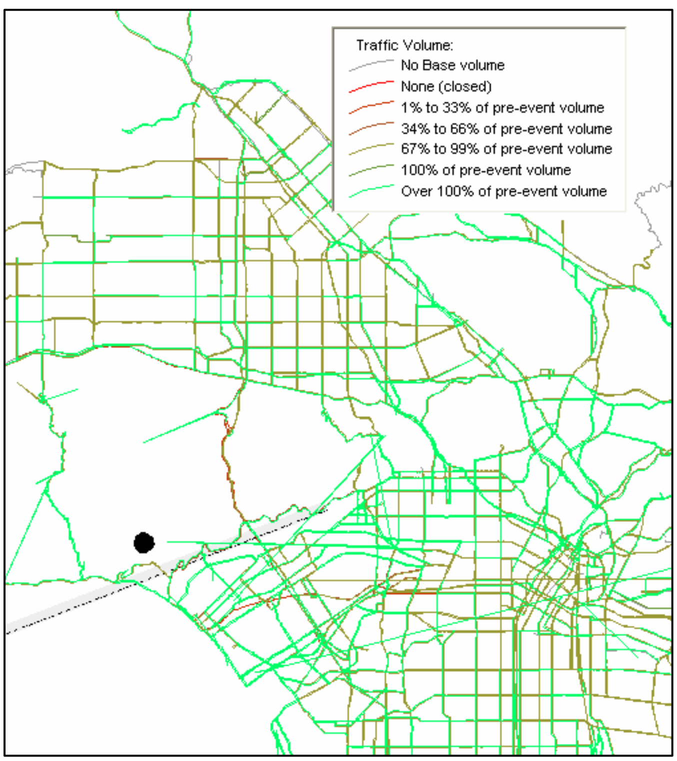
- ***System-Wide Post-Earthquake Travel Times (Fig. D-13).*** This set of maps shows how access and egress times to/from all of the TAZs in the region are affected by earthquake damage to this highway-roadway system. Output from this analysis provides these results for both automobile and freight traffic; and Figure D-13 shows the results for automobile traffic. 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.



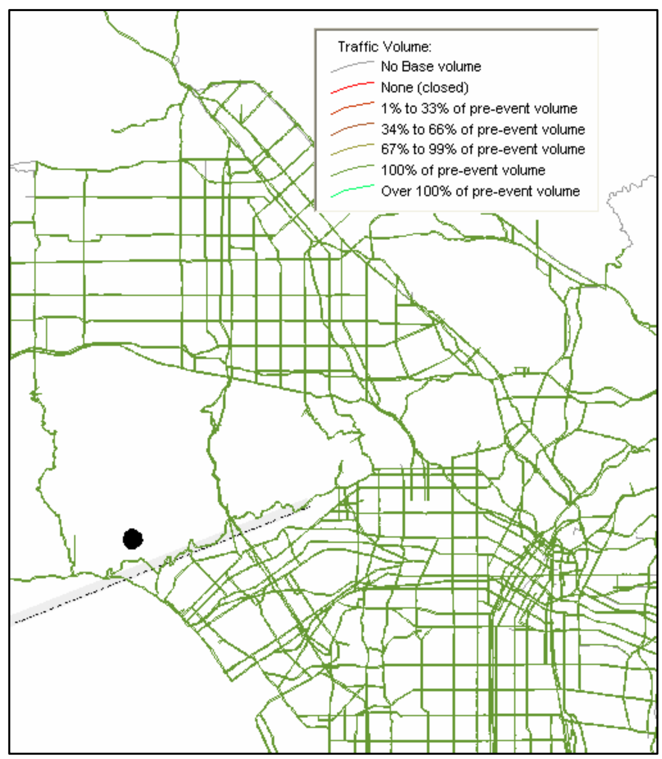
a) 7 Days after Earthquake



b) 60 Days after Earthquake

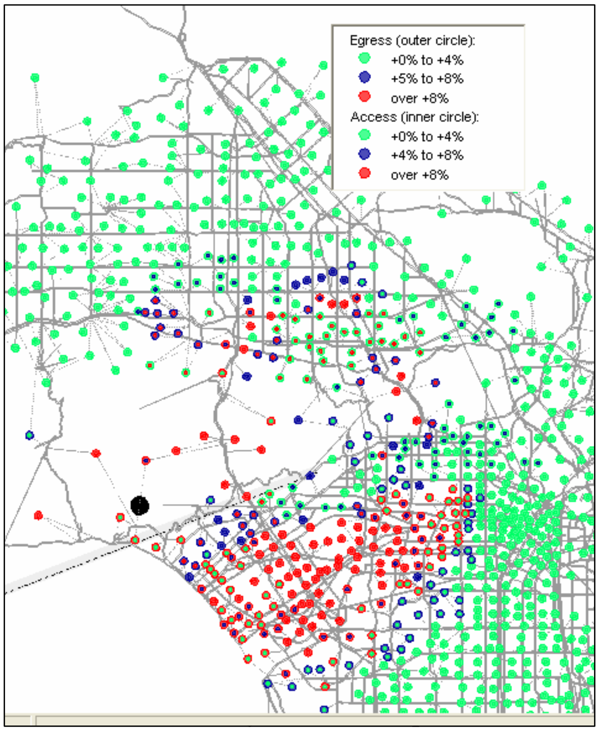


c) 150 Days after Earthquake

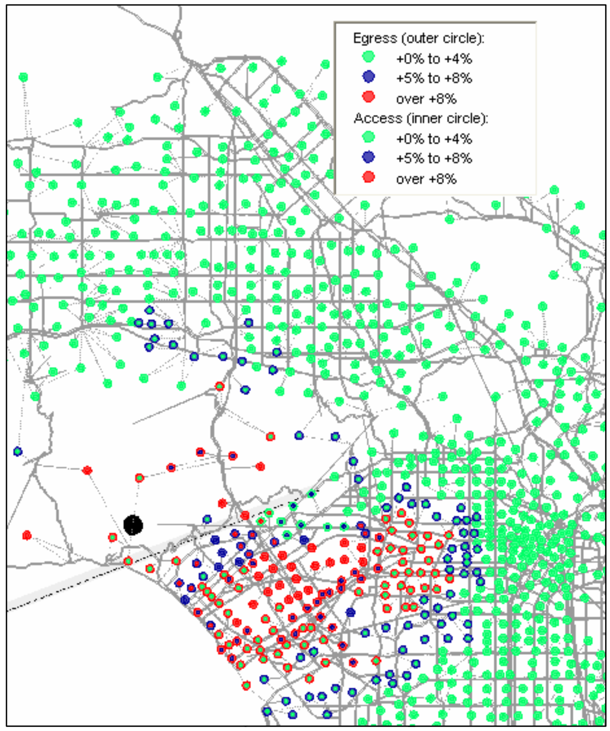


d) 221 Days after Earthquake

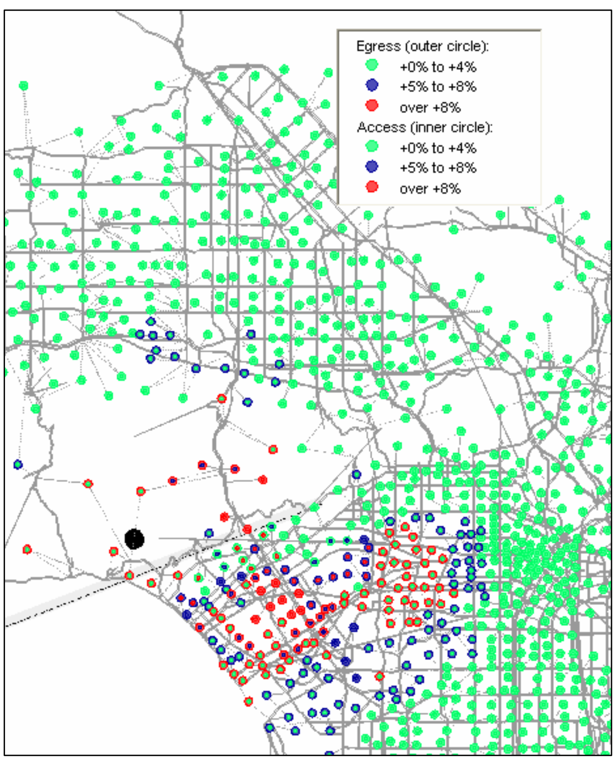
Figure D-12. Post-Earthquake Traffic Volumes (percentage of Pre-Earthquake Volumes)



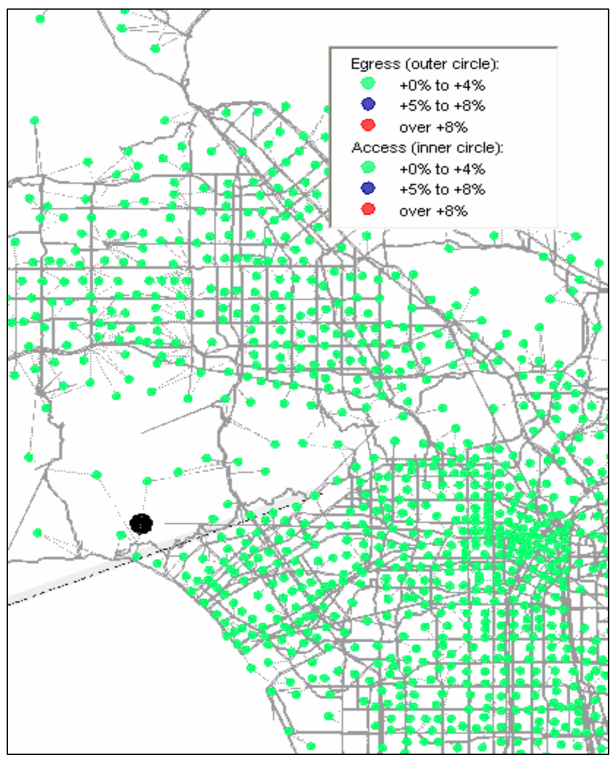
a) 7-Days after Earthquake



b) 60 Days after Earthquake



c) 150 Days after Earthquake



d) 221 Days after Earthquake

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

- ***System-Wide Post-Earthquake Trip Demands (Fig. D-14).*** This set of maps shows how automobile- and freight-trip demands on the LA-testbed highway-roadway system are affected by earthquake damage to the system. Figure D-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 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.

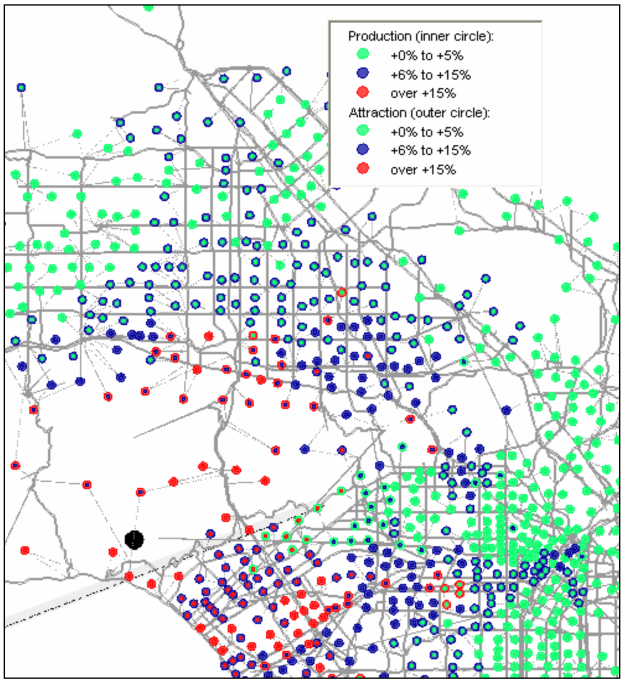
In addition to the above maps of system-wide traffic impacts, REDARS™ 2 provides additional detailed data on travel times and trip demands to/from user-designated key locations and along user-designated key routes. Tables D-4, D-5, and D-6 provide tabulations of: travel times and trips to/from the various locations shown in Figure D-5, as well as travel times along the particular routes shown in Figure D-6. The data from these tables can be helpful for emergency response planning. In addition, they indicate the distribution and extents of the traffic impacts throughout the highway-roadway system and, in this way, supplement the information provided in Figures D-12 through D-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 D-4 and D-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 D-5 that are closest to the most severely damaged segments of the I-10 and I-405 freeways.

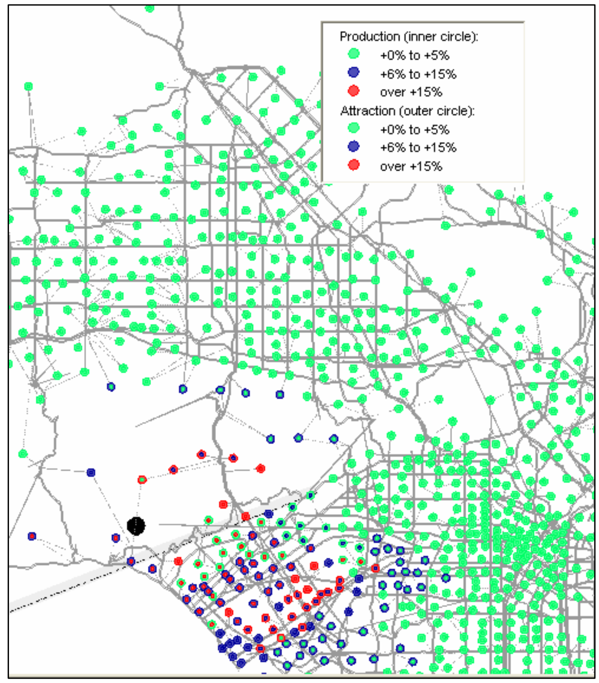
- However, the rather large travel-time and trip impacts for the Encino and North Hollywood TAZs are less intuitive in view of their greater distance from the severely damaged sections of the highway-roadway system. Therefore, it is necessary to further examine the data from Tables D-4 to D-6 in order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

- For example, Table D-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 as well.

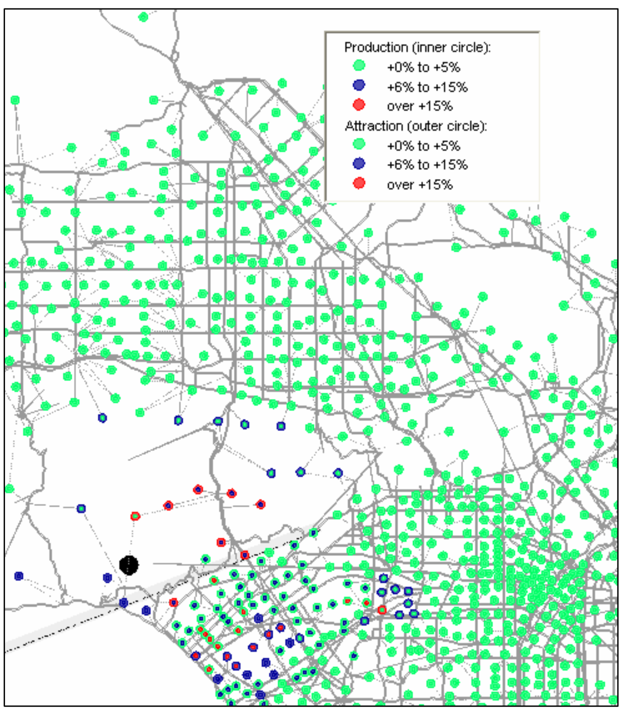
- From this, the following rationale for the above traffic impacts for the Encino and North Hollywood TAZs can be hypothesized: (a) the I-101 freeway parallels the I-10 freeway as a major route into the downtown-LA commercial center, and both of these freeways are heavily traveled; (b) thus, because of the severe damage along the I-10 freeway, many travelers that would ordinarily use that freeway as a route to downtown LA could 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 rather large 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, resulting in a net decrease in the number of trips along I-101 after the earthquake.



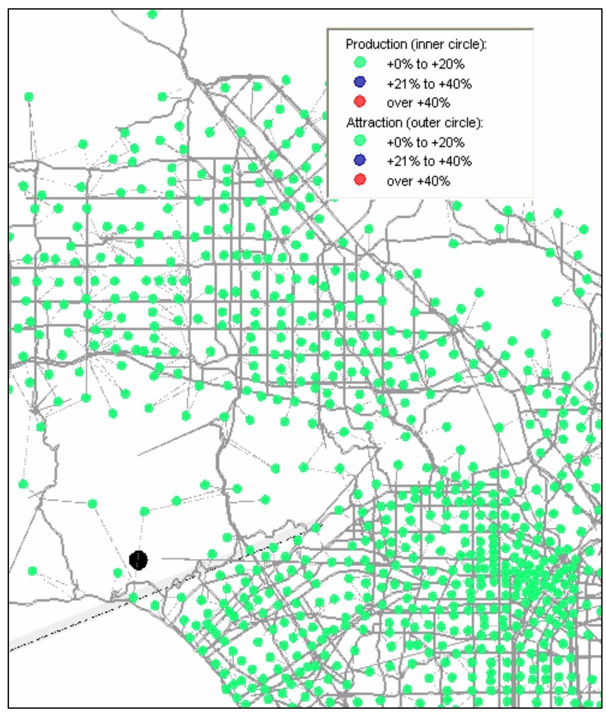
a) 7 days after Earthquake



b) 60 Days after Earthquake



c) 150 Days after Earthquake



d) 221 Days after Earthquake

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

Table D-4. Post-Earthquake Travels Time Increases for Traffic Analysis Zones shown in Figure D-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 D-5. Post-Earthquake Trips to/from Traffic Analysis Zones shown in Figure D-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 D-6. Post-Earthquake Travel Times along Key Routes shown in Figure D-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%

D.3.6 Economic Losses

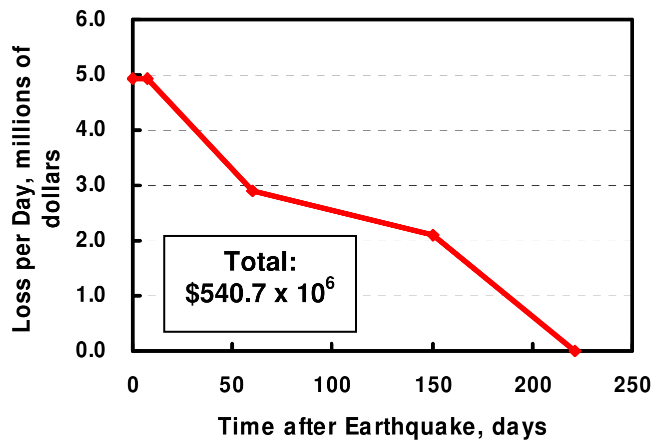
The REDARS™ 2 estimates of economic losses due to the earthquake damage to this highway-roadway system include repair costs, and losses due to travel-time delays, and trips foregone due to post-earthquake traffic congestion. The repair costs are estimated by applying the default bridge, approach-fill, pavement, and tunnel models that are described in Chapter 5 of this report. Losses due to travel-time delays and trips foregone are estimated by the procedures described in Chapter 6 and Appendix C.

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 described in Chapter 6 and Appendix C. These traffic impacts are, in turn, 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 D-7.

Table D-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 D-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 area shown in Table D-8.

Table D-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

D.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-roadway 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 in order 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 limits in the results are sufficient to justify termination the probabilistic analysis at that point.

D.4.1 <u>Probabilistic Output</u>

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

D.4.1.1 Seismic Performance of Overall Highway-Roadway System

REDARS™ 2 provides the following four types of output for use in characterizing the seismic performance of a highway-roadway 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-roadway 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 D-15 shows probabilistic estimates of economic losses developed during this LA-area demonstration application. Subsection D.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-roadway 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 D-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.

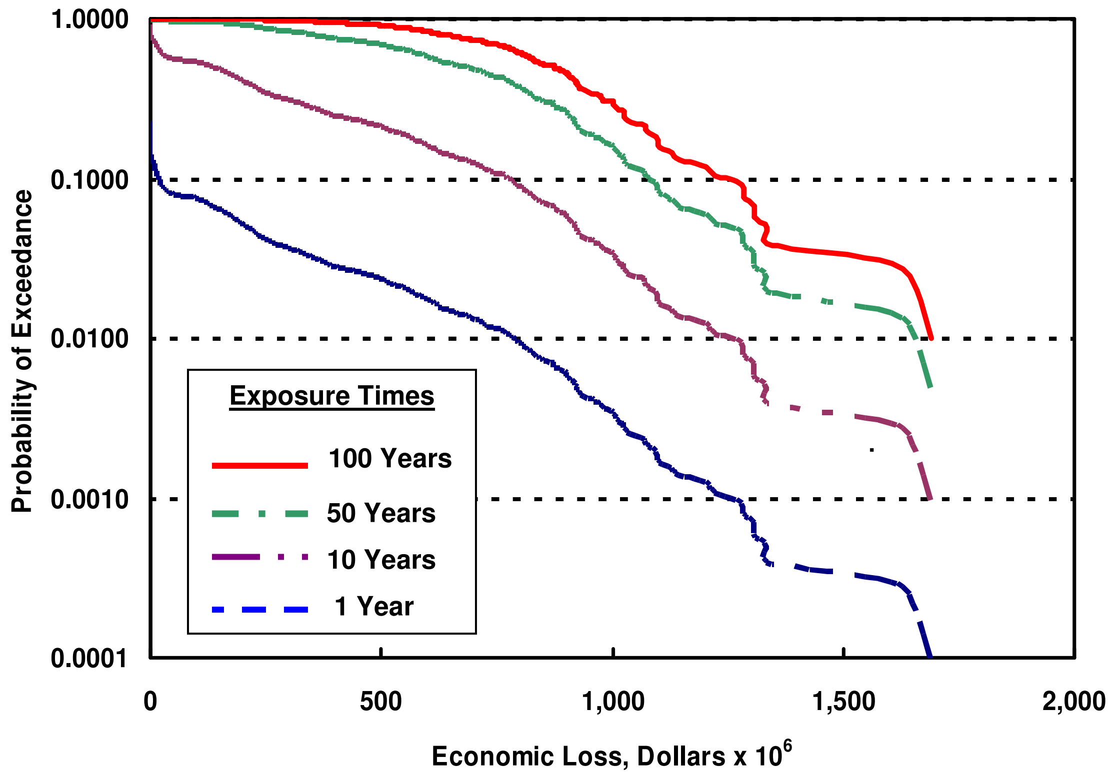
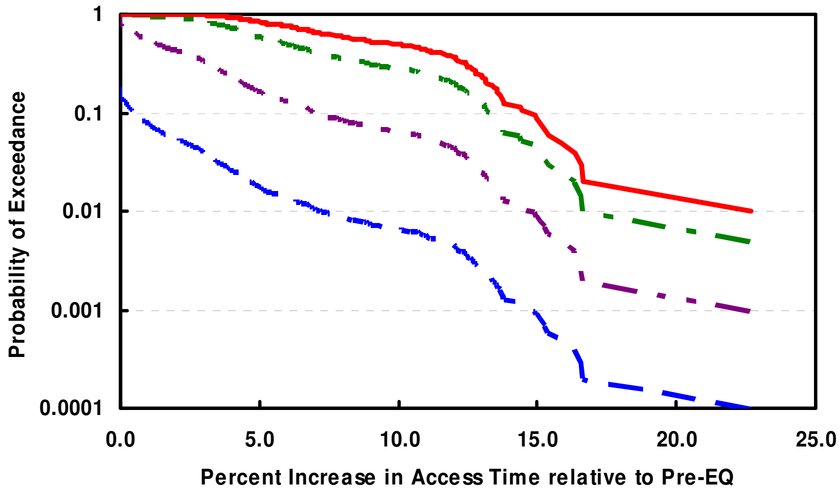


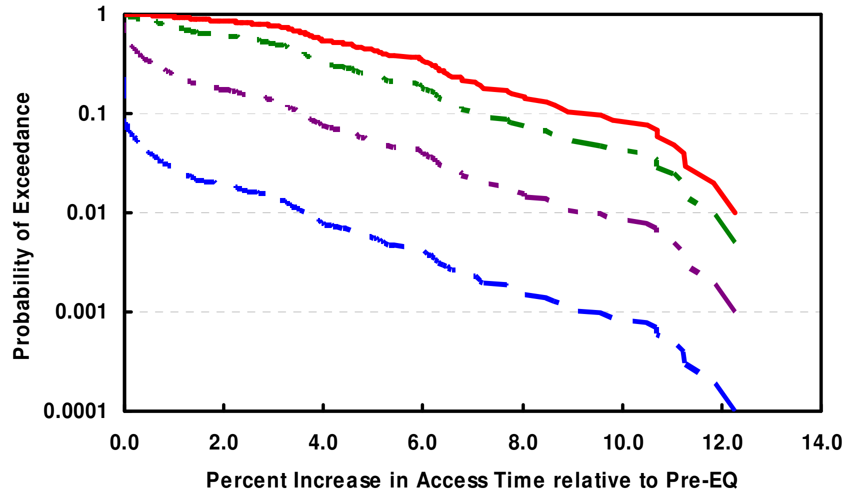
Figure D-15. Economic Losses

- ***Travel Times along Key Routes.*** Certain routes in an earthquake-prone region may be designated as "lifelines, which means they must remain functional to carry emergency vehicles after an earthquake. In addition, certain routes will be important for travel to/from a key location after an earthquake. Figure D-17 displays probabilistic estimates of travel time delays along I-405 between I-10 and I-105 (route (d) in Fig. D-6), which is an important link to/from the LA International Airport.[2].
- ***Trips to/from Key Locations***. Another possible impact of earthquake damage to a highway-roadway 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 D-18 displays probabilistic estimates of reductions in trips to downtown LA.

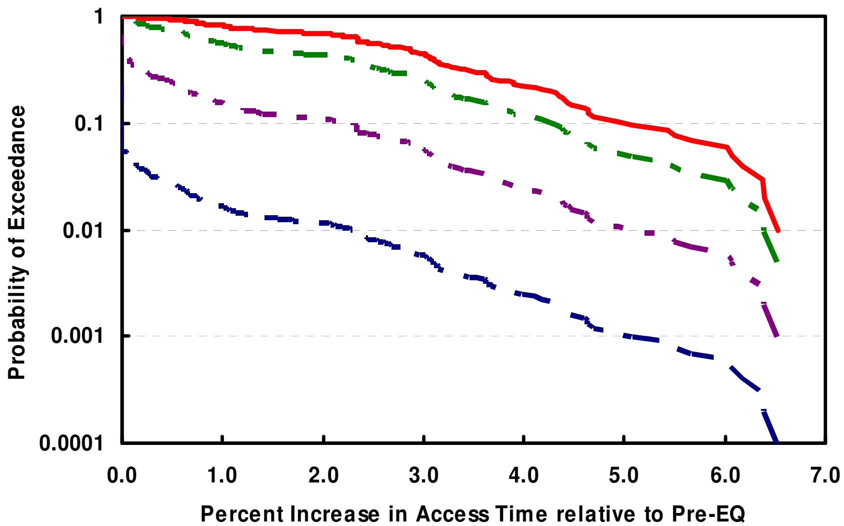
[2] Figure D-17 shows that, in some cases, there may a slightly negative increase in travel times along these routes (which is actually a travel-time decrease). This can occur when effects of reductions in trips along the route exceed the effects of travel-time increases due to actual damage to the segment. 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).



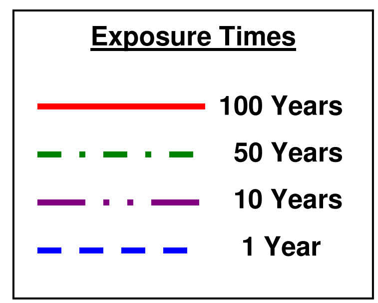
a) Time after EQ = 7 Days



b) Time after EQ = 60 Days

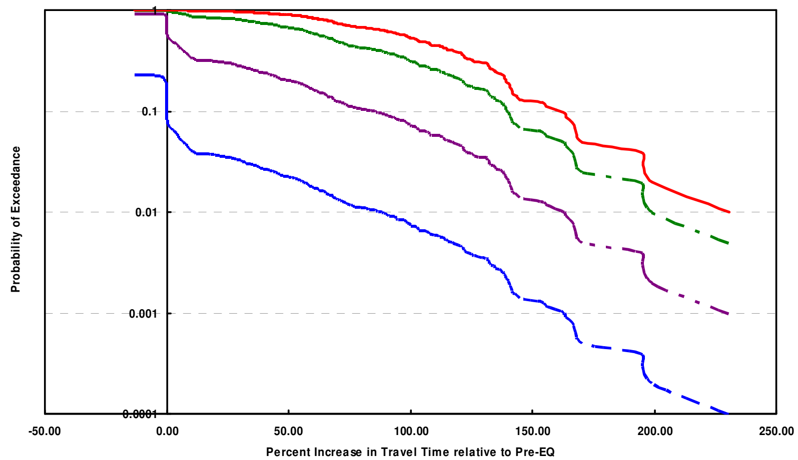


c) Time after EQ = 150 Days

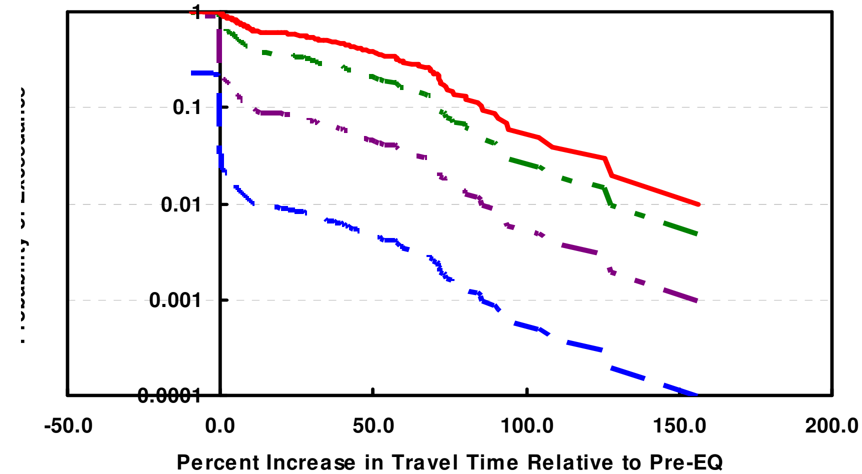


Note: At 221-days after EQ, system returns to pre-EQ state (percent increase in travel time = 0.0)

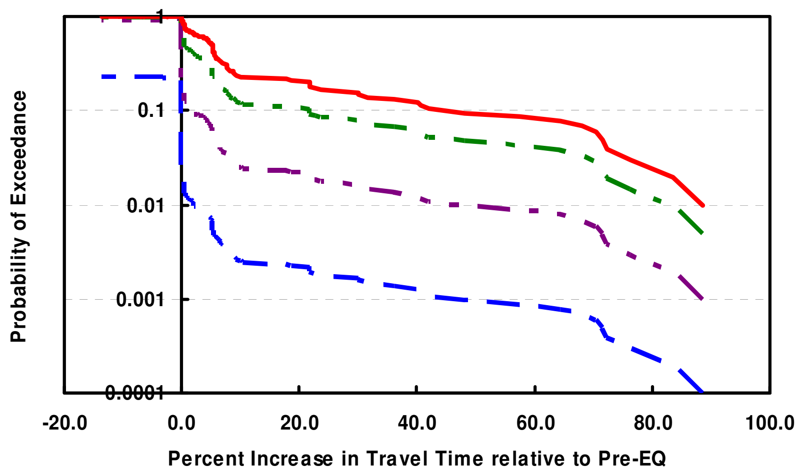
Figure D-16. Percent Increase in Access Times to UCLA Medical Center



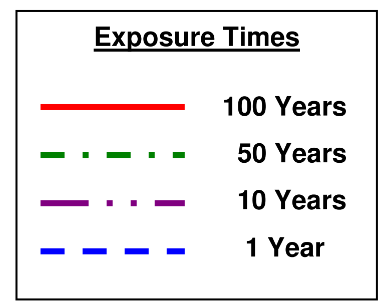
a) Time after EQ = 7 Days



b) Time after EQ = 60 Days

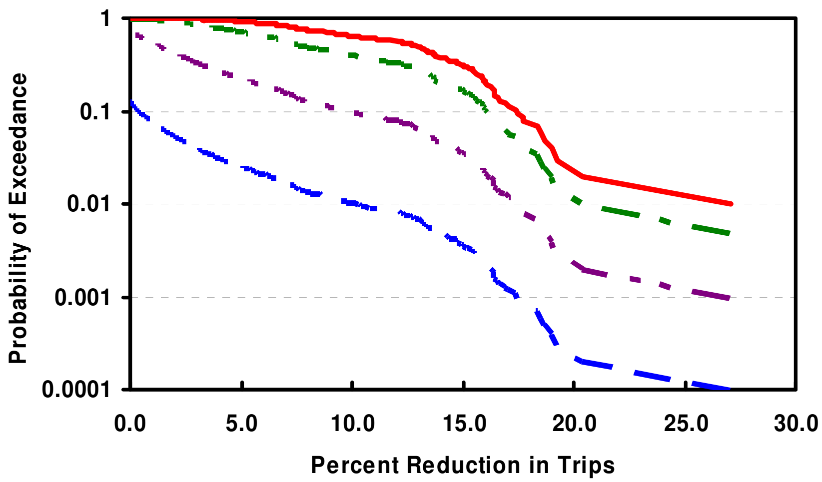


c) Time after EQ = 150 Days

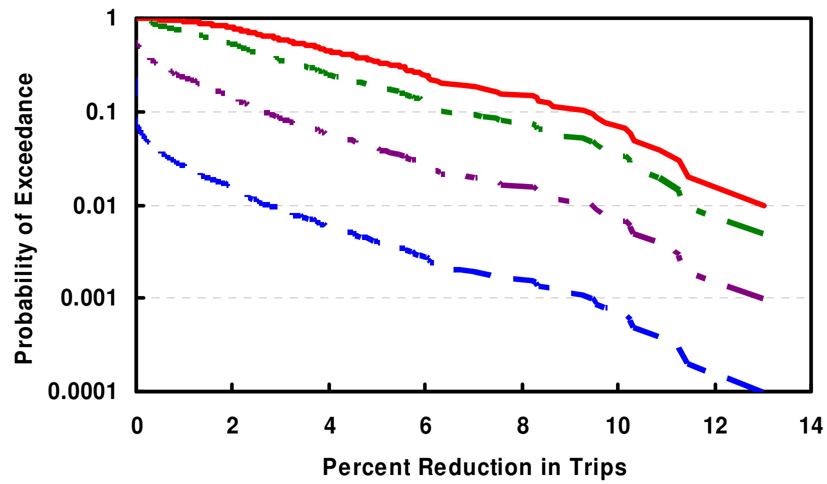


Note: At 221-days after EQ, system returns to pre-EQ state (percent increase in travel time = 0.0)

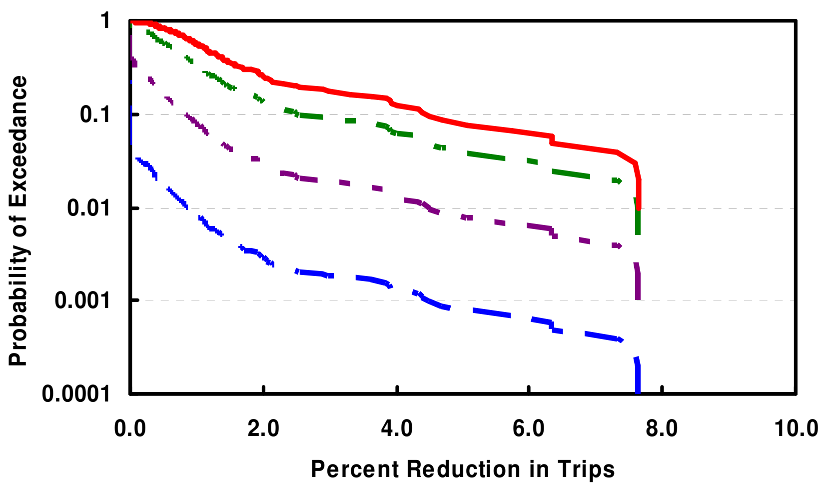
Figure D-17 . Percent Increase in Travel Time along I-405 between I-10 and I-105 (Key Route to LA International Airport)



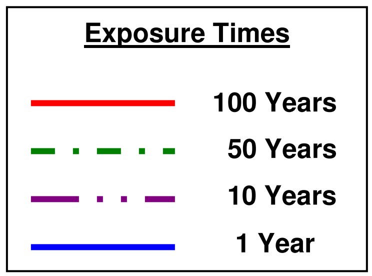
a) Time after EQ = 7 Days



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 reduction in trips = 0.0)

Figure D-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-roadway 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. D.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 REDARS™.

D.4.1.2 Seismic Performance of Individual Components within Highway-Roadway System

For highway-roadway 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 D-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-roadway 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 that have the highest probability of collapse. Use of this information, along with REDARS™ SRA results that indicate each bridge's importance to overall system-wide traffic flows, provides a sound basis for establishing bridge-retrofit priorities.[3]

Figures D-20 and D-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 D-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-roadway system .

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

[3] REDARS™ 2 is not yet able to provide system-wide bridge-collapse probability maps of the type shown in Figure D-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.

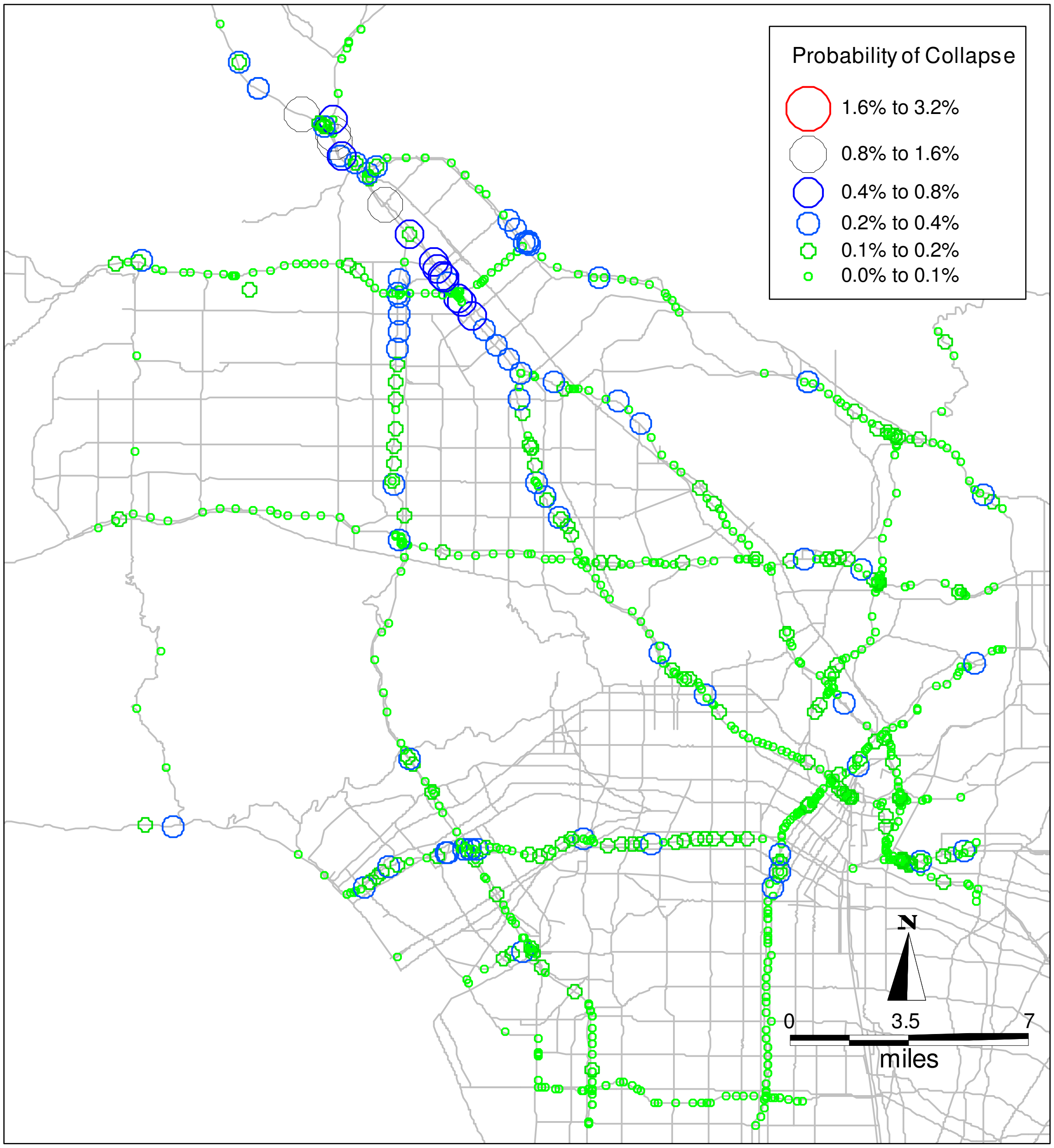


Figure D-19. LA-Area Highway-Roadway System Map showing Those Bridges with the Highest Probability of Collapse.

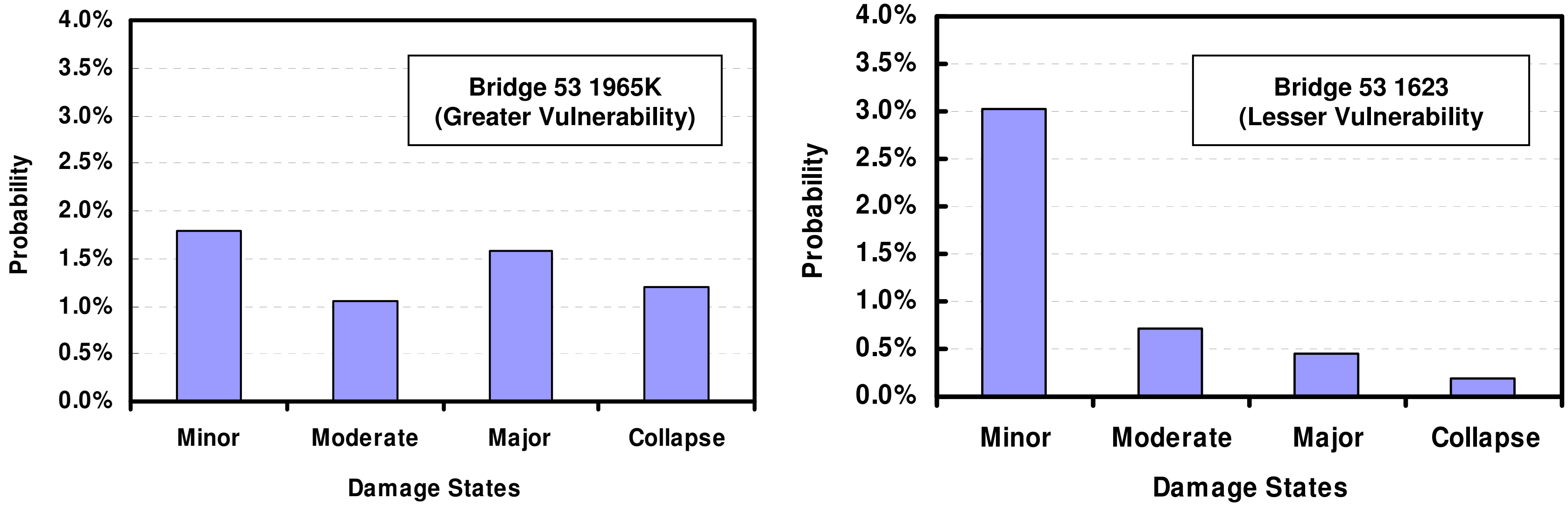


Figure D-20. Probability Bar Charts for Bridges with Different Degrees of Vulnerability

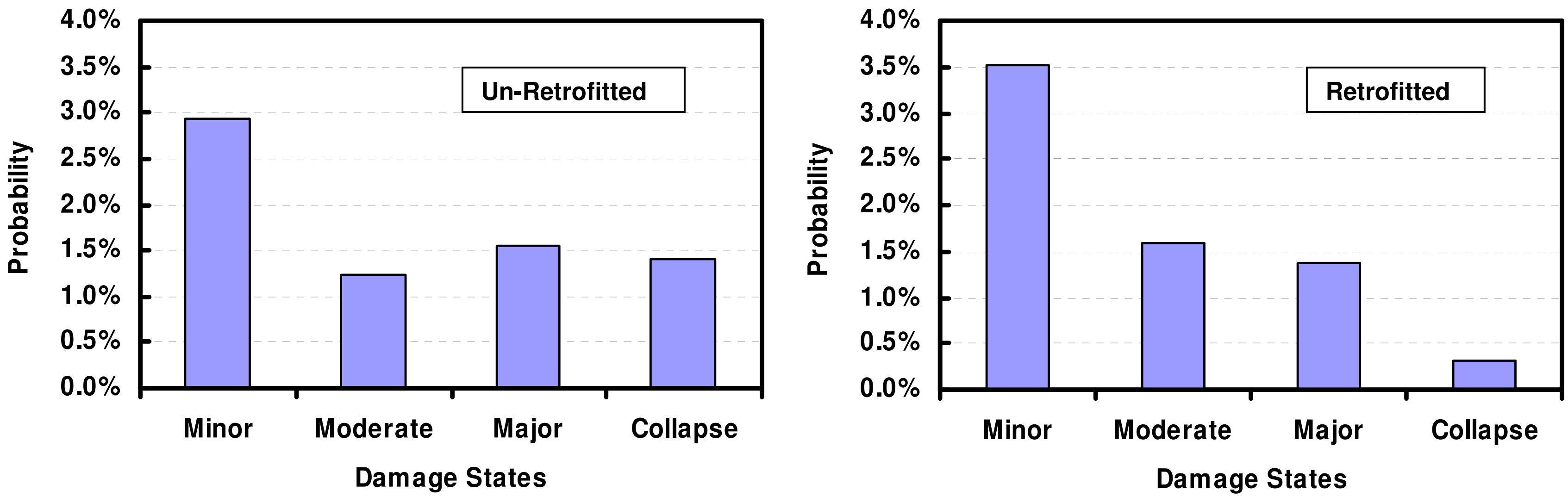


Figure D-21. Probability Bar Charts for Un-Retrofitted and Retrofitted Bridge 53 1984L

D.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 D-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.

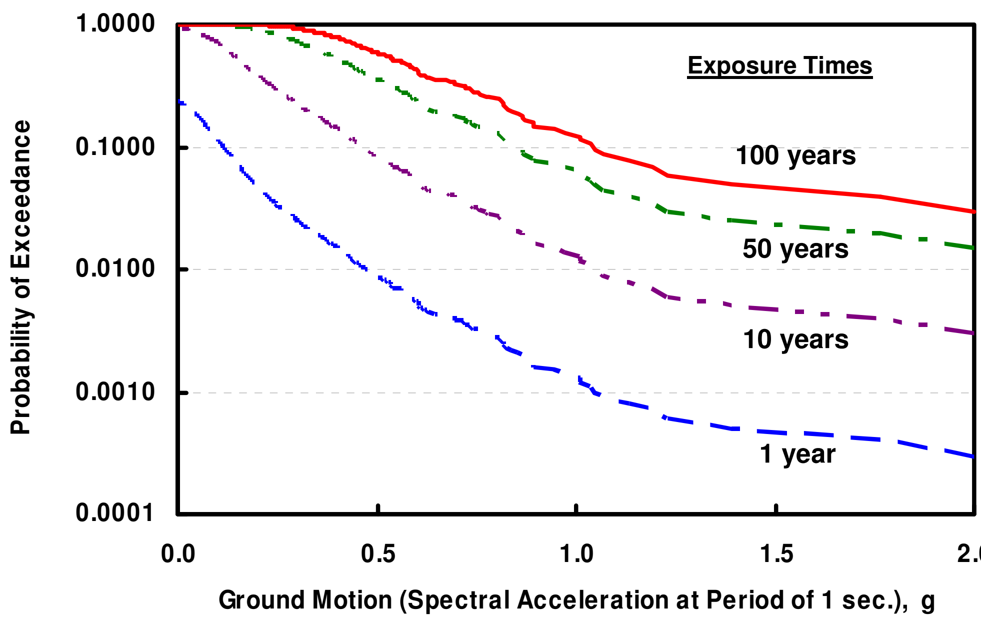


Figure D-22. REDARS™ 2 Probabilistic Ground-Motion Estimates at Bridge 53 1318 in LA-Testbed Highway-Roadway System

D.4.2 Convergence Checks

D.4.2.1 Background

As noted in Chapter 2, the REDARS™ 2 SRA methodology and software uses a Monte Carlo process to develop statistically sound probabilistic SRA results. It also includes a check of statistical confidence intervals in the AAL results as the analysis for each successive damaging earthquake in the walkthrough table is analyzed. If the REDARS™ 2 user judges that an acceptable confidence interval has been achieved after some intermediate number of damaging earthquakes 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 all damaging earthquakes in the walkthrough table were analyzed. To facilitate this check of convergence intervals, an advanced and efficient statistical analysis procedure -- the variance-reduction method that is described in Appendix J -- has been developed under this project and programmed into REDARS™ 2.

The probabilistic SRA of the LA-testbed highway-roadway system that is described in Section D.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 used for this analysis (see Section D.2.6). When the analysis was completed for each successive earthquake, updated confidence intervals were computed and stored. Section D.4.2.2 shows how these confidence intervals converged as the analysis proceeded through each year of the walkthrough table.

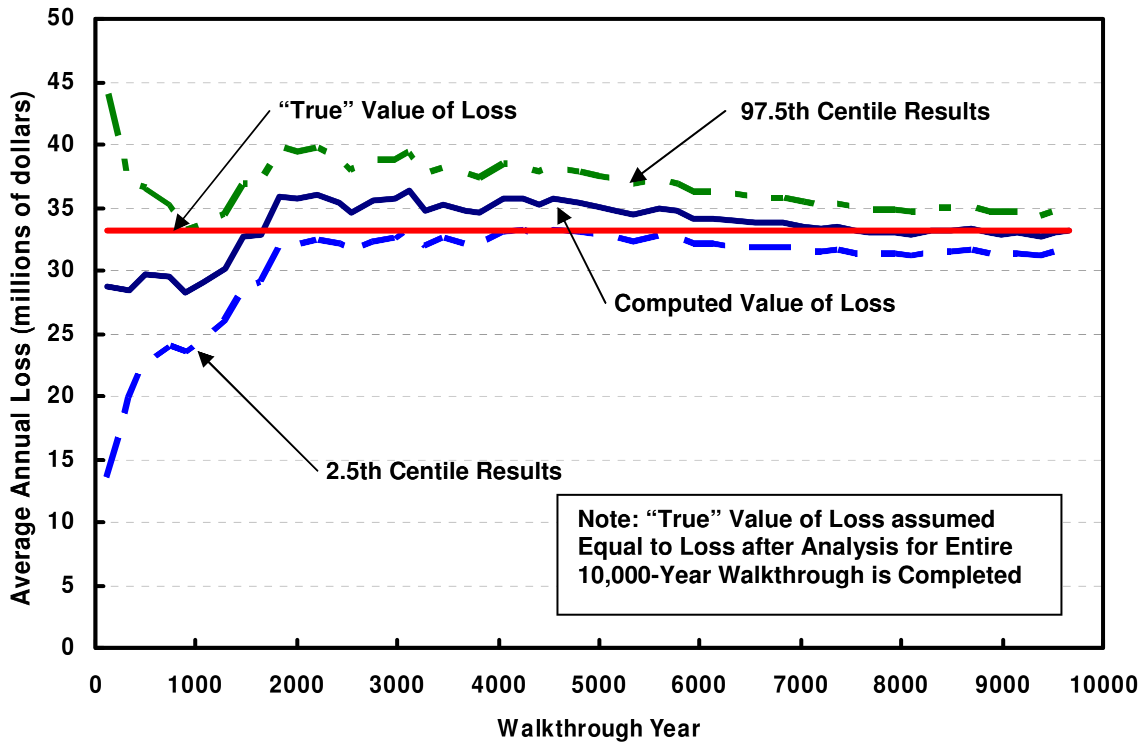
D.4.2.2 Results

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".

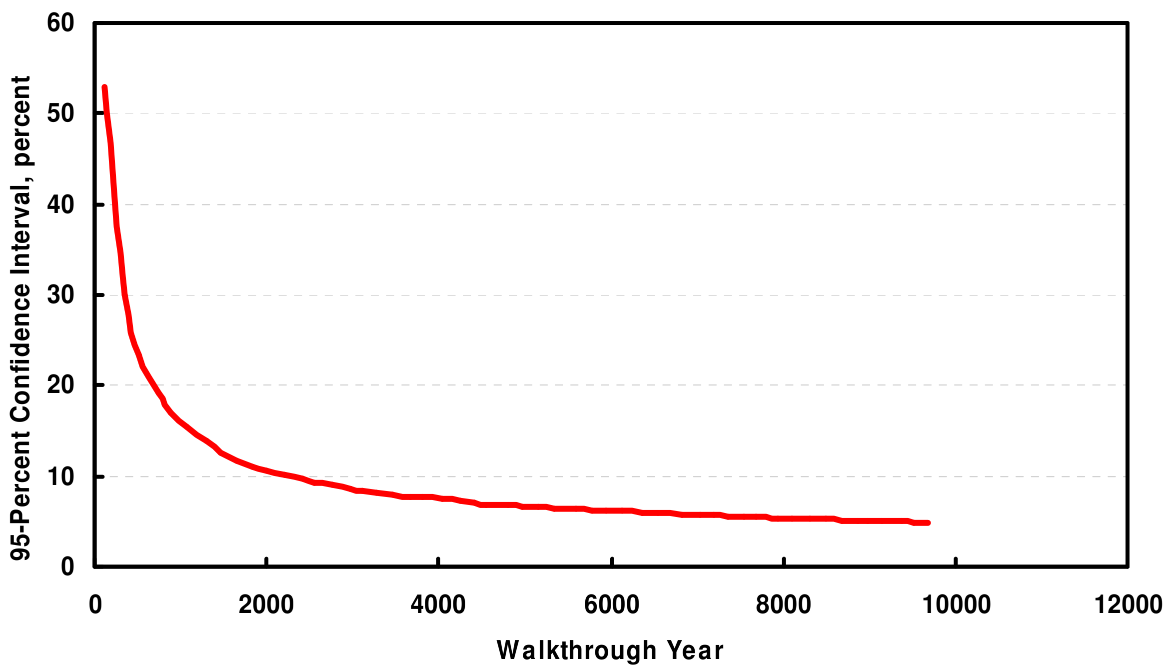
Two forms of results were developed in this convergence check. The first, which is shown in Figure D-23a, is in the form of a "funnel test" which visually shows how the confidence interval about the computed and "true" values of the AAL, improve as the number of walkthrough years increases. In this, 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 D-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. Investigation of confidence intervals for such other parameters is a task to be addressed under future projects to further develop and upgrade REDARS™ 2 (see Chapter 8)
.



a) Funnel Test



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

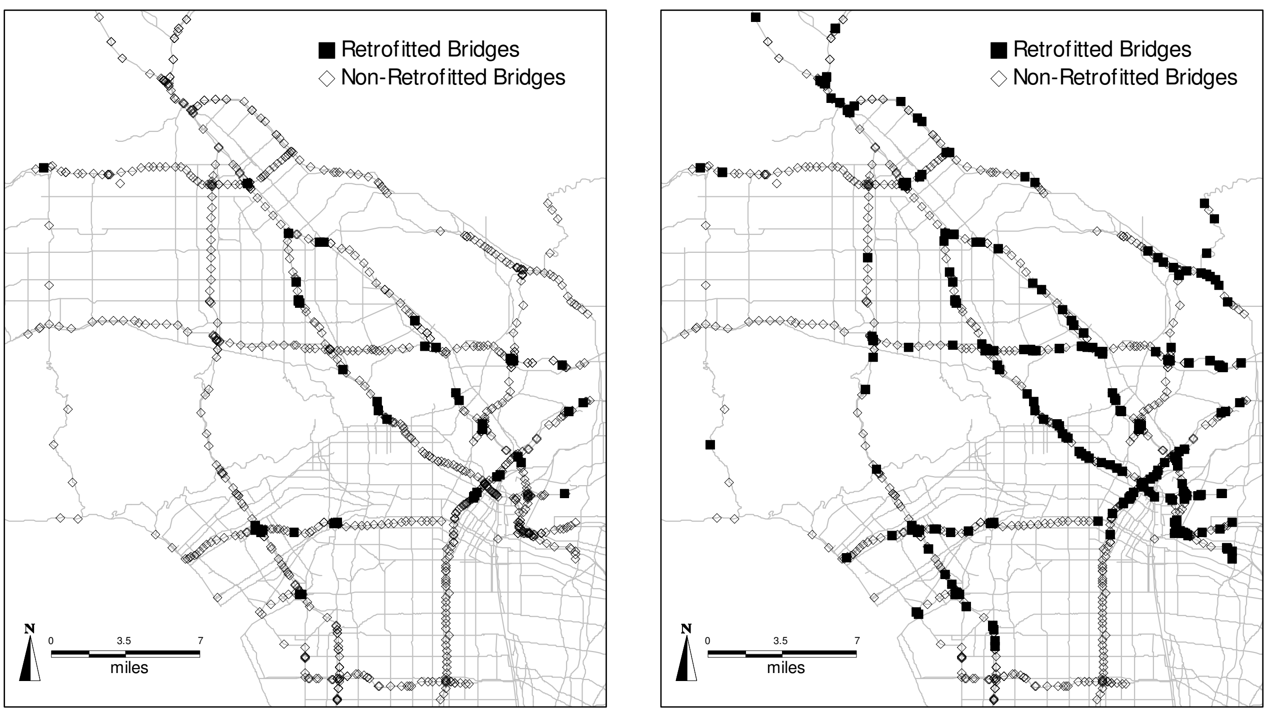
Figure D-23. Confidence Intervals for Results of Probabilistic SRA of LA-Testbed System

D.5 EXAMPLE ECONOMIC ANALYSIS OF A BRIDGE RETROFIT PROGRAM

D.5.1 <u>Background</u>

This section provides an example of an approach for using REDARS™ 2 probabilistic assessments of economic losses (Sec. D.4.1.1) in order to 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.

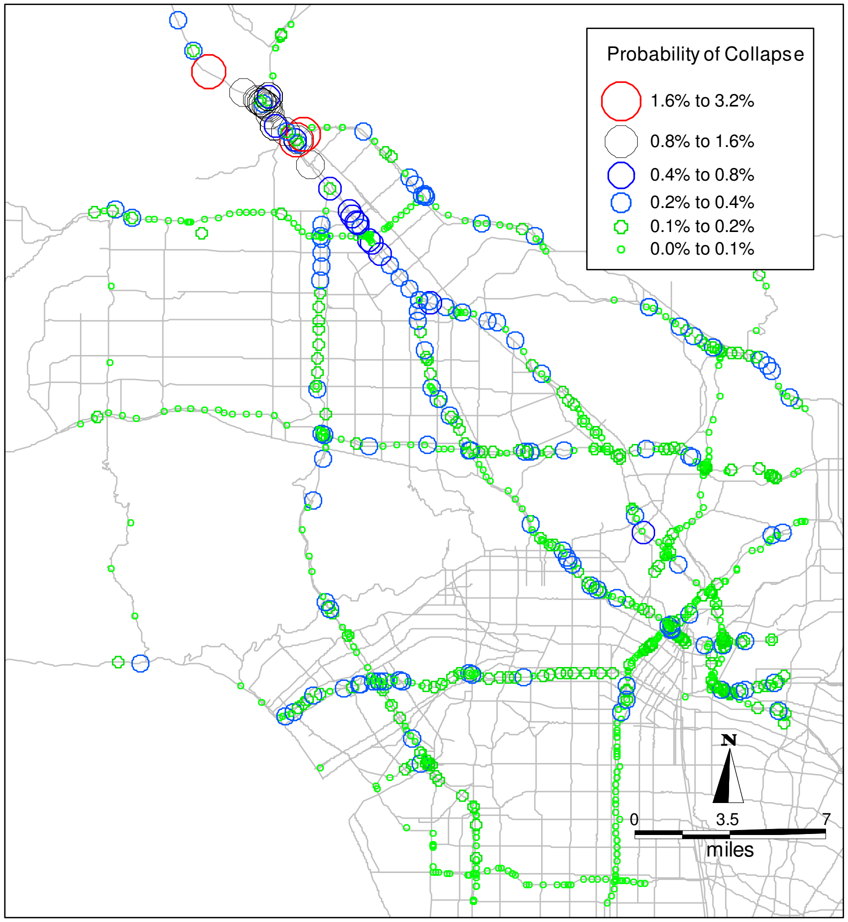
This economic analysis considers only those bridges that are located in the LA-testbed system and, in addition, only those bridge retrofits that have been carried out within this system since the 1994 Northridge Earthquake and up to the end of 2004. Within this system, 57 bridges had actually been column 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 that time (Yashinsky, 2005). Figure D-24 shows the locations of the retrofitted bridges throughout the LA-testbed system, before and after these 231 bridge retrofits were completed, and Figure D-25 provides REDARS™ 2 analysis results that indicate how these retrofits have reduced the probabilities of collapse of the bridges throughout this system



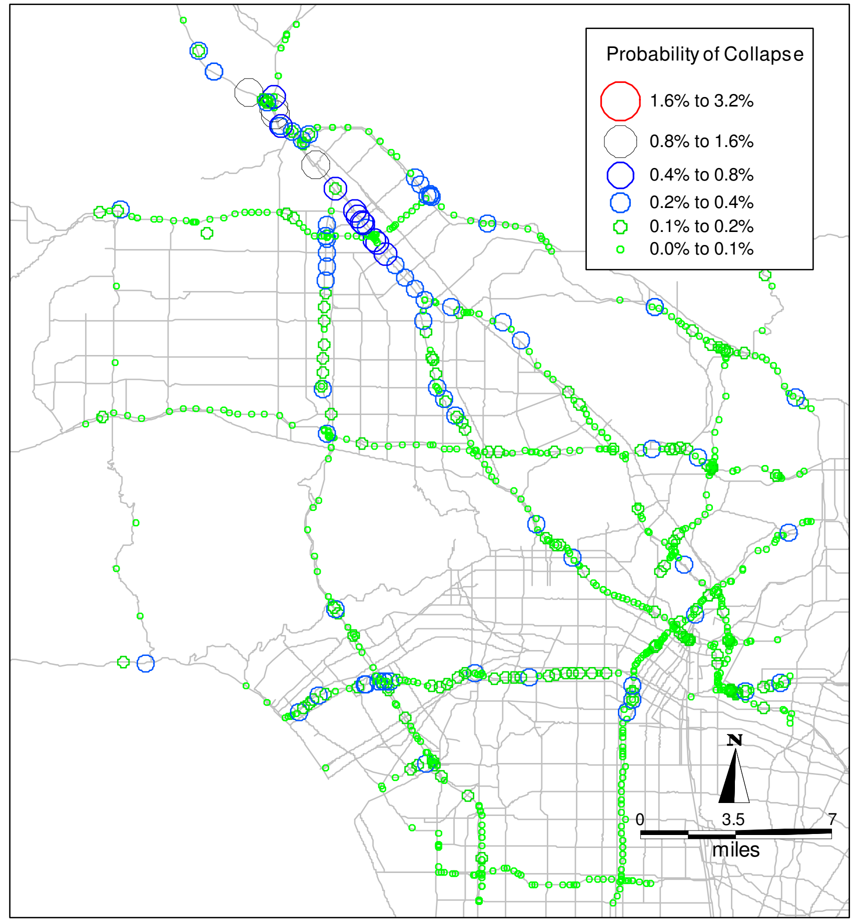
a) System Prior to Northridge Earthquake (early 1994)

b) System as of End of 2004

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



a) As of Early 1994, shortly after Northridge Earthquake



b) As of end of 2004

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

D.5.2 <u>Suppositions</u>

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.

D.5.3 <u>Analysis Approach</u>

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-roadway 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.

D.5.3.1 Estimation of Retrofit Costs

The costs of these retrofits were estimated from data provided by Caltrans (Bailey, 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.

D.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. D-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. D-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 D-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.

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

In this example, *PVL* is computed for a range of plausible exposure times and discount rates.

D.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 D.5.3.1).

D.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.

D.5.4 Results

D.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-roadway 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 addition, discount rates of the order of 2.5% and 4% have been common in recent years. Previously, discount rates of about 7% have been most representative. Each of these discount rates was used in the benefit-cost calculations, which are summarized in Table D-9 below.

Table D-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

Table D-9 shows benefit-cost ratios of about 2.4 for the older discount rate of 7%, 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% are used. These results indicate that the retrofit of these 231 bridges was a cost-effective investment in seismic risk reduction.

D.5.4.2 Standard Deviation of Losses

Table D-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 D-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% 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-roadway 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 of this report.

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

Over the past 12 years, the Federal Highway Administration (FHWA) has funded two seismic research projects (each with a six-year duration) that have been directed and conducted by the Multidisciplinary Center for Earthquake Engineering Research (MCEER).

The first of these projects, titled *Seismic Vulnerability of Existing Highway Construction*, was carried out during the 1993-2000 time period. It focused on the development of: (a) seismic retrofit and evaluation methodologies for existing highway-roadway systems and structures; and (b) improved seismic design criteria and procedures for these structures. One of the major tasks from this project was to develop a new methodology for seismic risk analysis (SRA) of highway-roadway systems that addressed the various issues raised in Section 1.1. This methodology, which was named REDARS™, used data and models from geosciences (seismology and geology), engineering (structural, geotechnical, and transportation), component repair and reconstruction experience, transportation network analysis, and risk analysis, to develop deterministic and probabilistic estimates of the seismic performance of highway-roadway systems. In this, the 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-roadway system in Shelby County, Tennessee (Werner et al., 2000).

Following the completion of this first project, a second six-year FHWA-MCEER project was initiated. This project, which built on developments from the first project and was titled *Seismic Vulnerability of the Highway System*, performed studies to improve the earthquake resistance of bridges and highways, through the development of new and improved methods for component seismic retrofit and for predicting the seismic performance of highway systems and components. As part of this project, the prior work on the REDARS™ SRA technology during the first project was further developed by updating several of the REDARS™ models and modules from the first project, and developing the REDARS™ technology into a public-domain software package that can by used to assess the seismic performance of highway systems nationwide. After this software (named REDARS™ 2) was developed, it was used to analyze the seismic performance of the Los Angeles highway-roadway system, in order to demonstrate the types and forms of its various results. This project work was completed during March 2006, and is documented in a series of reports and manuals by Werner et al. (2006) and Cho et al. (2006a and 2006b).

1.3 PROJECT OBJECTIVE

This current project has been supported by the California Department of Transportation (Caltrans) and is titled *REDARS™ Demonstration Project*. Its main purpose has been to enable Caltrans' staff to assess the applicability of the REDARS™ technology and software to Caltrans' future seismic-risk-reduction programs statewide. This has been accomplished through the close collaboration of Caltrans' staff with the team of engineers, programmers, transportation network analysts, and risk analysts that has worked together in developing the REDARS™ 2 software under the FHWA-MCEER project, and hereafter is referred to as the REDARS™ Development Team (RDT). The collaboration focused on:

- Enabling Caltrans' staff to systematically evaluate emerging SRA technologies and to gain an understanding of the REDARS™ 2 SRA methodology and software;

- Enabling the RDT to improve the REDARS™ methodology and software for California applications by developing a California-based earthquake model, an improved transportation network analysis procedure, and an improved component module; and.

- Enabling Caltrans' staff to use this improved software in a demonstration application of this updated REDARS™ software (termed REDARS™ 2) to a Northern California testbed highway-roadway system that is located within eastern and northern segments of the San Francisco Bay area. This application has also served as a beta test of REDARS™ 2 by the Caltrans project staff.

1.4 PROJECT SCOPE

This project was initiated in July 2003 and was completed in June 2006. To enable the project to meet the above objectives, it was organized into the following technical tasks:

- ***Task 1. REDARS™ Usability Planning for California Applications.*** Under Task 1, the RDT worked with Caltrans' engineering, planning, programming, and management personnel to address key issues related to output, seismic risk reduction decision making, and software standards that are key to the adaptation of REDARS™ 2 to meet Caltrans' particular needs.

- ***Task 2, Updated Hazards Module for California Applications.*** Under Task 2, the RDT provided technical support to Caltrans' staff during their evaluation and selection of models for characterizing earthquake occurrences, ground motion hazards, liquefaction hazards, and surface-fault-rupture hazards. In addition, the RDT programmed the selected models and incorporated them into the REDARS™ 2 software.

- ***Task 3. Updated Component Module for California Applications.*** Under Task 3, the RDT carried out the following subtasks: (a) they worked with Caltrans' staff to guide their understanding of procedures for developing user-specified fragility curves for bridges; (b) they calibrated the HAZUS99-SR2 fragility models for bridges subjected to ground shaking hazards against bridge damage observations during the Northridge Earthquake, and modified these models to incorporate retrofitted bridge performance and to also substantially improve comparisons between model-damage predictions and earthquake-induced damage observations; and (c) they collaborated with Caltrans' engineering and maintenance staff to develop bridge repair models and tunnel, approach-fill, and roadway-pavement vulnerability models that represent Caltrans' post-earthquake bridge repair experience, as well as their construction, seismic design, and repair practices for these component types.

- ***Task 4. Updated System Module for California Applications.*** Under Task 4, the RDT modified the prior REDARS™ network model to enable it to: (a) make trip demands responsive to network delays that will result from earthquake-induced damage and reduced traffic-carrying capacity of the network; and (b) incorporate traffic flows from freight-carrying trips throughout the roadway network. In addition, the RDT compiled input data for freight flows in the Bay Area for use in Caltrans' application of the REDARS™ 2 testbed highway-roadway system under Task 6 of this project.

- ***Task 5. Input Database Needs for California Applications.*** Under Task 5, the RDT guided Caltrans' staff during their development of input data for the testbed highway-roadway system that they analyzed under Task 6, and also identified certain anomalies in Caltrans' statewide databases for highway-roadway systems and component locations and attributes.

- ***Task 6. Seismic Risk Analysis of Testbed Highway-Roadway Network.*** Under Task 6, the RDT supported Caltrans' implementation of their SRA of the Northern California highway-roadway system from the eastern and northern portion of the San Francisco Bay area. As noted earlier, these applications also constituted Caltrans' beta testing of REDARS™ 2.

- ***Task 7. Project Advisory Panel Meetings.*** A key part of this project has been periodic meetings with a Project Advisory Panel (PAP). This Panel, which is comprised of experts and end users, has served to advise Caltrans as to the quality of the research conducted under this project, and whether the progress being made under this project has been satisfactory. During these PAP meetings, the RDT presented information on the project objectives, progress, and end results, and participated in discussions with PAP members that enabled the PAP to assess the REDARS™ project work and direction.

1.5 REPORT ORGANIZATION

The remainder of this report is organized into eight main chapters and four appendices. Chapter 2 contains a description of the REDARS™ SRA methodology, in order to provide readers with the necessary background for enabling readers to comprehend and interpret the remainder of the report. The remaining seven chapters (Chapters 3 through 9) describe the procedures and results for Tasks 1 through 7, as summarized in Section 1.4.

The first two appendices of the report describe the framework for the REDARS™ 2 probabilistic SRA (Appendix A) and REDARS™ 2 Import Wizard which, like Chapter 2, provide necessary background information for readers of the report. Then, the remaining two appendices describe the latest upgrades of the REDARS™ 2 transportation network-analysis procedure (Appendix C), and a demonstration application of REDARS™ 2 to the Los Angeles area highway-roadway system that was developed under the FHWA-MCEER project and is provided here as a reference for future users of REDARS™ 2 within Caltrans .

It is noted that prior to the preparation of this report, an overall technical manual for REDARS™ 2 was recently developed under the FHWA-MCEER project in order to provide detailed descriptions of the various procedures, modules, and models that comprise this SRA methodology (Werner et al., 2006). This manual was developed to serve as a technical reference for all future users of REDARS™ 2, and includes significant procedures and results developed under this Caltrans project as well as the FHWA-MCEER project. Therefore, those sections of the manual that describe relevant developments from or background for this Caltrans project are also included in this final report.

CHAPTER 2
SEISMIC RISK ANALYSIS METHODOLOGY

2.1 OVERVIEW

REDARS™ 2 enables users to carry out deterministic or probabilistic SRA for any user-defined roadway system nationwide, according to the methodology shown in Figure 2-1. For probabilistic SRA (which is based on the framework described in Appendix A), results are developed for multiple simulations -- in which a "simulation" is defined as a complete set of system SRA results for one set of randomly selected input 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 multi-disciplinary 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 roadway 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 (the number, type, origin, and destination for all trips that use the roadway system.

- ***Losses.*** Consequences of earthquake damage to the roadway system, including: (a) economic impacts (repair costs and losses due to travel time delays); (b) increases in travel times and reductions in trip attraction/production to/from designated key locations (e.g., hospitals); 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 desirable 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 roadway system, the seismic hazards, the seismic performance of the components, and the economic losses due to earthquake-induced damage 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. These modules are further described in Section 2.3.

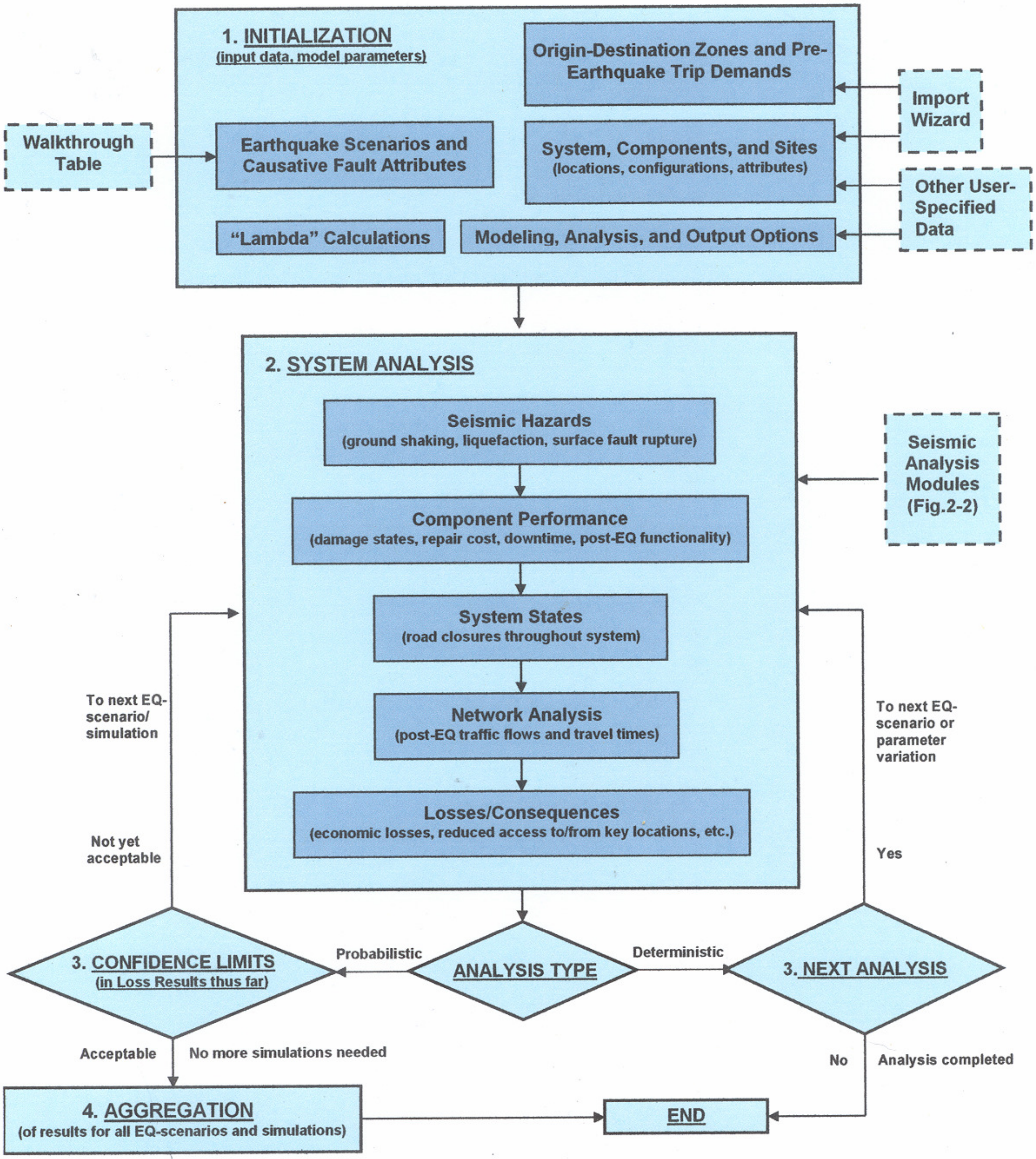


Figure 2-1. REDARS™ 2 Methodology for Seismic Risk Analysis of Roadway Systems

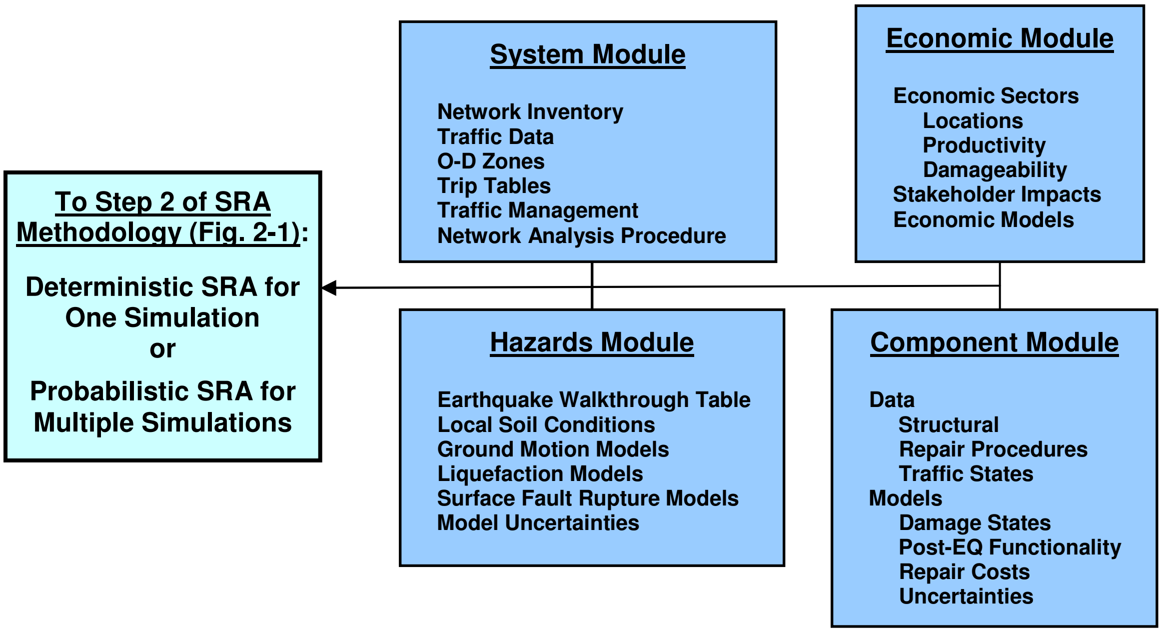


Figure 2-2. REDARS™ 2 Seismic Analysis Modules

- ***Multidisciplinary.*** The SRA methodology synthesizes models developed by earth scientists, geotechnical and structural earthquake engineers, transportation engineers and planners.

- ***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 (that now includes the effectiveness of each option in reducing post-earthquake traffic congestion and travel times). Results can also be developed for use in post-earthquake emergency response in real time (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 provided. 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, which is based on the variance-reduction statistical analysis procedure that is described in Taylor et al. (2004) and in Werner et al. (2006), can substantially reduce analysis times for probabilistic SRA applications.

- ***Import Wizard.*** To carry out SRA of roadway systems, publicly available databases and certain user-specified 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. However, experience has shown that use of these databases can be time consuming due to various data inconsistency and connectivity issues that often arise. Therefore, REDARS™ 2 includes an "Import Wizard" to facilitate the use of these databases by: (a) accessing the various databases; (b) guiding the user though the application of these databases to develop input data for the user-selected study region; (c) resolving any inconsistencies between data from any of the databases; and (d) checking the resulting roadway network model and the connectivity and continuity of the O-D zones. The Wizard is further described in Appendix B and in Cho et al. (2006a).

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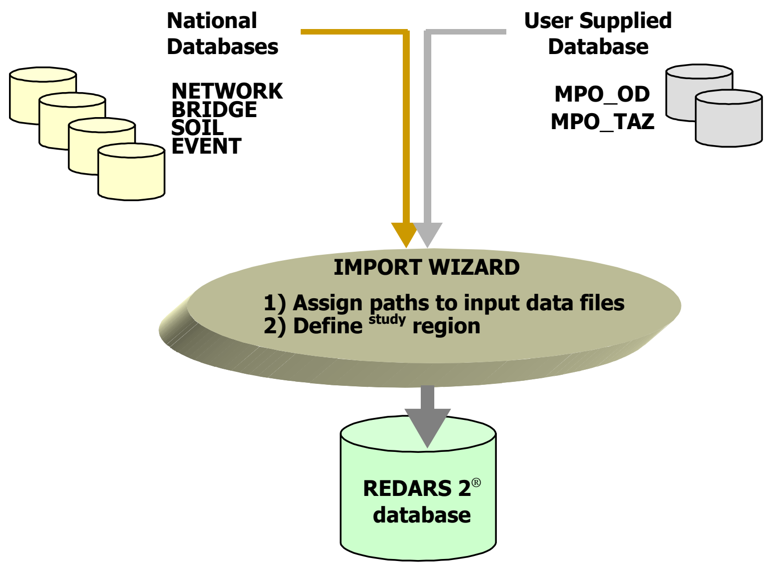

Figure 2-3. Development of REDARS™ 2 Input Data from Publicly Available Databases

2.3 SEISMIC ANALYSIS MODULES

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

2.3.1 System Module

The system module contains input data and models for characterizing the roadway 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 roadway 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 flows (e.g., detour routes, changing roadways from two-way to one-way traffic, etc.); and (e) any special system characteristics, such as certain roadways 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 cognizant Metropolitan Planning Organization (MPO) for the region being investigated, in order to obtain data defining 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 data bases, as shown in Figure 2-3) and then processes all of these data in order to provide them in a form for direct input into the roadway system 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 cognizant state, county, and 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 roadway 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 estimates reductions in trip demands due to increased congestion from earthquake damage to the roadway system; (c) it accommodates various types of trips along the roadway system (i.e., trips via automobile, via various types of freight trucking, etc.) by enabling the user to specify separate trip tables for each trip type; (c) it uses a numerically efficient minimum-path algorithm to reduce computer times for estimating post-earthquake traffic flows.

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 roadway 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

The input data contained in the Hazards Module to evaluate the seismic hazards consist of: (a) the scenario earthquake events to be considered in a probabilistic application of REDARS™ 2, in the form of a "walkthrough table" that specifies earthquake occurrences over time in accordance with established earthquake models for the region[1] (see Section 4.2); (b) local soil conditions throughout the system, as needed to estimate local geologic effects on ground shaking and the potential for liquefaction; and (d) locations and characteristics of any faults within the system that have a potential for surface rupture. Charter 4 further describes these input data.

[1] Deterministic SRA applications can consider an earthquake from the walkthrough table, or an earthquake with any user-specified magnitude and location.

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 4 and in Werner et al. (2006).

2.3.2.2(a) Ground Motion Hazards

For each scenario earthquake and simulation, ground motion hazards are estimated at the site of each component in the roadway system. The models used to obtain these estimates 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. 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.

2.3.2.2(b) Liquefaction Hazards

After the ground motion hazards are estimated at each potentially liquefiable site in the roadway system, liquefaction hazards at these sites are then estimated. In this, the potentially liquefiable sites within the system must be identified beforehand by the REDARS™ 2 user, from his/her geologic screening of site soil conditions and topography throughout the system. Then, for each potentially liquefiable site that is identified, permanent ground displacement (PGD) hazards (lateral spreading and vertical settlement) are evaluated for each scenario earthquake, using models that include effects of uncertainties and account for 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 near the ground surface, PGD hazards are estimated at those roadway-system sites that fall within the fault rupture's zone of deformation. These estimates use input data that define fault-rupture attributes (location, orientation, type, rupture plane dip and directions) and the earthquake's magnitude and location within the rupture plane. From this, each component near the fault rupture is assessed to estimate whether it actually falls within the rupture's zone of deformation. For sites within this zone, PGDs are estimated, including effects of uncertainties.

2.3.3 Component Module

2.3.3.1 Overview

The Component Module contains input data and models for estimating: (a) (a) each component's seismic response to site-specific ground shaking and to PGD hazards 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 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. These end results of these estimates consist of 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 5 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 are provided as 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 deterministic 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 those modeling those particular 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 roadway 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 the large volumes of interstate trucking traffic that pass over those bridges (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 roadway 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 solely on the data for bridges nationwide that are provided by 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 5. 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-roadway 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 roadway-system's network model in order to develop overall post-earthquake "system states" at each of these times. The system states consist of modified roadway 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 can 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, as well as the component's location within the system. These system states are used by the REDARS™ 2 network-analysis procedure that is described in Chapter 6 and Appendix C, in order to estimate system-wide travel times and traffic flows at each post-earthquake time.

2.3.4 <u>Economic Module</u>

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 (e.g., effects on businesses, stakeholders, and the regional/national economy) are excluded. This model is described in Werner et al. (2006).

2.4 ANALYSIS PROCEDURE

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

2.4.1 <u>Step 1. Initialization</u>

Step 1 involves the development of input data that defines: (a) the roadway 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 roadway 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 B and in Cho et al. (2006a).

2.4.1.2 Walkthrough Table Data

Earthquake scenarios are provided in terms of a walkthrough table that defines, for each year over a total duration that can be on the order of thousands or tens-of-thousands of years, the number of earthquakes occurring during that year, the location of each earthquake and whether it is caused by fault rupture or is an areal event, the moment magnitude of each earthquake, and, for all fault-based earthquakes, 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, earthquake walkthrough tables have been developed for Coastal California and for the Central United States region that surrounds the New Madrid seismic zone. Section 4.2 describes the development of the Coastal California walkthrough table, which can be used in Caltrans' future applications of REDARS™ 2

2.4.1.3 Other User-Provided Data

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

2.4.1.4 "Lambda" Calculations

If the SRA is to be probabilistic (and after the above roadway, component, soils, and earthquake data are entered), REDARS™ 2 carries out an analysis that counts the number of 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 when 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 <u>Step 2. System Analysis</u>

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 motions 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-time delays and trips foregone; (b) access/egress times and trip production/attraction for those particular locations (TAZs) that were identified under Step 1; and (c) travel times along 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. This network-analysis procedure is further described in Chapter 6 and Appendix C of this report.

- *Economic Impact Evaluation.* The data and models from the Economic Module are applied to the above post-earthquake travel-time delays, 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 an advanced statistical analysis procedure termed a "variance-reduction" method to estimate confidence intervals (CIs) for the results from all simulations developed thus far. These CIs are then displayed after each successive simulation for consideration by the user. If the user decides that these CIs are not yet acceptable, the SRA then develops additional simulations by repeating the system analysis under Step 2 for additional earthquake scenarios and additional sets 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.

2.4.4 Step 4. Aggregate Results

If the SRA is probabilistic, Step 4 compiles results from all simulations are compiled and develops probabilistic aggregations of these results. Such probabilistic results can be developed for: (a) economic losses due to roadway 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 reductions in trip attraction/production for any location (TAZ) that was previously identified under Step 1; and (e) travel time increases along any route that was previously identified under Step 1. When these aggregations are completed, the probabilistic SRA is completed.

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 decision-making process for establishing appropriate pre- and post-earthquake seismic-risk-reduction programs for a highway-roadway system.

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 2-3 and are described in the remainder of this section. The demonstration application of REDARS™ 2 to an actual highway-roadway system that is described in Appendix D illustrates how REDARS™ 2 results can be used in this way.

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 roadway 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 roadway 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.

2.5.1 Step 1. Identify Seismic-Decision Options

Under Step 1, the various options that are open 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.

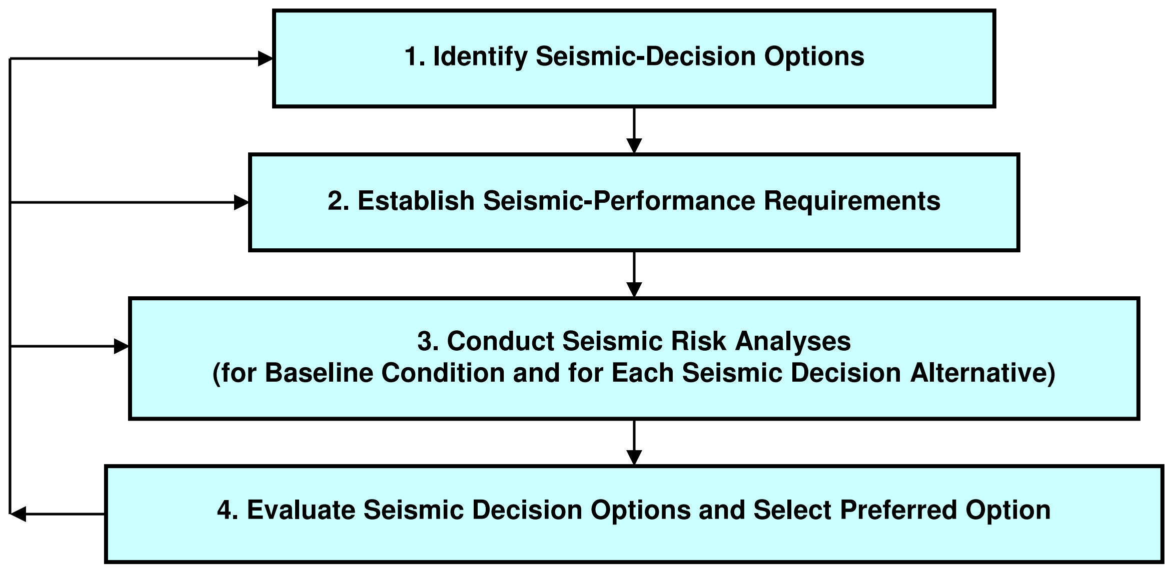


Figure 2-3. Use of SRA Results for Seismic-Risk-Reduction Decision Making

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 options. This selection can consider input from stakeholders in the seismic performance of the roadway 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 roadway 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 travel times to/from commercial centers and/or trip production/attraction for these centers.

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 roadway-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 trip demands.

When defining acceptable-risk levels and corresponding seismic-performance requirements, one must consider initial implementation 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 is based on the total life-cycle cost for each seismic-decision option which, as previously noted, is computed as the present value of: (a) the initial cost for implementing the option (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 times and reduced trip demands.

- 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 option, as obtained from probabilistic SRA of that option for each scenario earthquake and simulation.

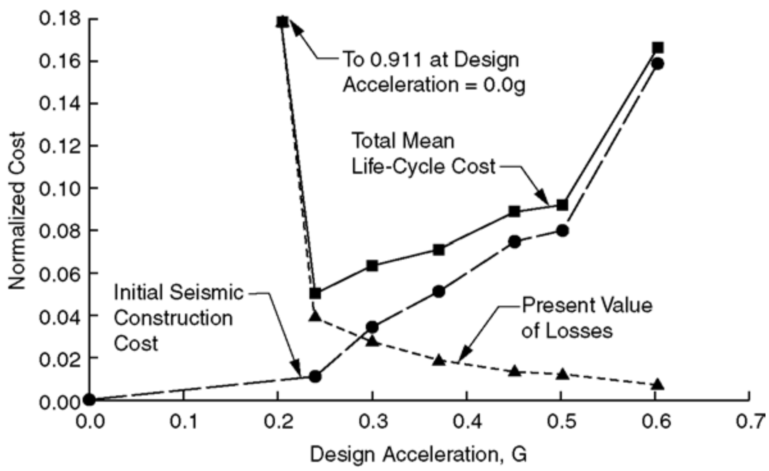
- Seismic-decision options are treated as alternative "investments" in seismic risk reduction. One basis for evaluating an investment is in terms of its financial yield. In this SRA application, a higher "yield" of an investment in seismic risk reduction is viewed being analogous to minimizing the mean 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 2-4 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).

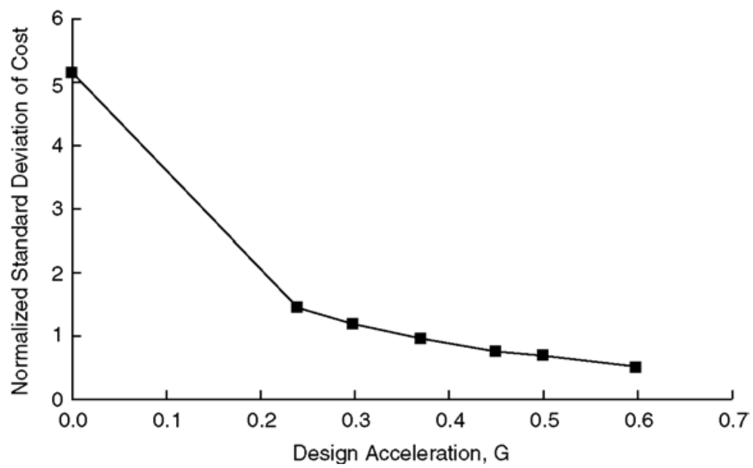
- Figure 2-5 shows how SRA results can be used to guide the establishment of priorities for retrofit of a several bridges within a highway system. In this, alternative priorities are evaluated in terms of the means and standard deviations of the resulting total costs. The dashed line in this figure shows those prioritization plans with the most favorable combinations of mean and variance (i.e., the lowest values of these quantities).

2.5.3 Step 3. Conduct Seismic Risk Analyses

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



a) **Mean Value of Total Life-Cycle Cost**



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

Figure 2-4. Selection of Design Acceleration for a Wharf Structure (Werner et al., 1999) [10]

2.5.3.1 Baseline System Performance

The SRA application starts with development of baseline system performance results, which are results before any seismic decision options are considered. These results should consist of:

- *Pre-Earthquake Performance of Existing Roadway System.* The transportation network-analysis procedures in the SRA methodology are used to assess the pre-earthquake traffic flows, travel times, and costs of travel for the existing (undamaged) roadway system.

- *Post-Earthquake Performance of Existing Roadway System.* Scenario earthquakes are applied to the existing roadway system (before any seismic decision options are considered), and SRA is carried out to evaluate post-earthquake travel times, trip demands, and travel costs.

- *Baseline Results.* Comparison of the roadway system's pre- and post-earthquake performance will indicate the risks that could occur in the absence of seismic risk reduction.

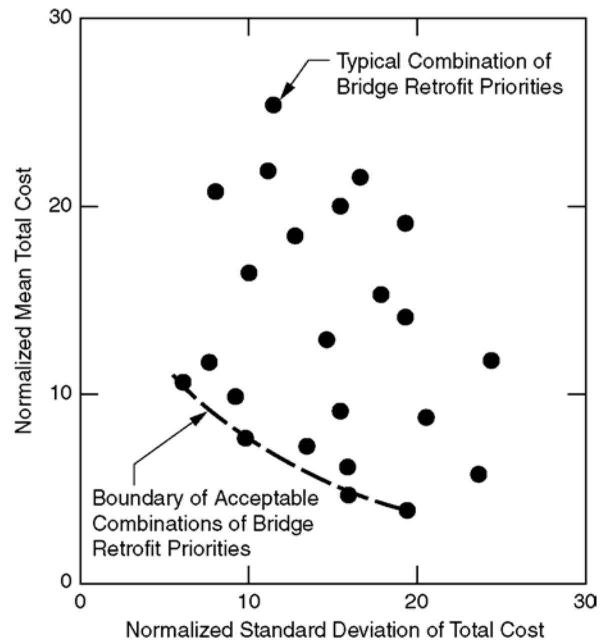


Figure 2-5. Illustrative Results for Evaluation of Alternative Bridge Retrofit Priorities

2.5.3.2 Post-Earthquake System Performance for Each Option

Once the baseline system performance results are developed, it remains to carry out SRA of the highway system after each seismic-decision option 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 options in Step 1. Then, SRA of the roadway 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 roadway 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 under consideration.

2.5.4 Step 4. Assess Seismic-Decision Options and Select Preferred Option

Under Step 4, the SRA results for the baseline (existing) condition and for each seismic-decision option are evaluated and compared. From this, a preferred option 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 options 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 options. If this occurs, one or more of the previous steps of the procedure may need to be repeated (see Figure 2-3).

CHAPTER 3
TASK 1: USABILITY PLANNING FOR CALIFORNIA APPLICATIONS

3.1 OBJECTIVE

Under Task 1, the REDARS™ Development Team (RDT) reviewed software standards, output needs, and seismic risk reduction decision making needs with Caltrans' project staff during the RDT's initial planning and development of software specifications for the REDARS™ 2 software (Geodesy, 2004). The purpose of this review at this very early stage of the RDT's software planning and development effort was to assure that the REDARS™ 2 software would: (a) be consistent with Caltrans software standards; (b) facilitate the development of input data for application to California highway-roadway systems; and (c) provide output that meets Caltrans' seismic-risk-reduction planning and emergency-response needs.

3.2 SOFTWARE

3.2.1 Operating System

Caltrans does not have any firm standard regarding software operating systems. In view of this, it was decided that REDARS™ 2 would be a stand-alone Microsoft Windows desktop application that would be designed and tested for Windows 2000 and XP operating systems.

3.2.2 Graphical Information System (GIS)

The RDT and Caltrans' project staff considered two options for providing GIS capabilities in REDARS™ 2 -- either incorporation of a license-free internal GIS capability into REDARS™ 2, or programming of REDARS™ 2 as an add-on to the ESRI ArcView GIS software. This latter strategy was previously adopted for the HAZUS public-domain software that estimates earthquake- and flood-induced losses to buildings and a wide variety of facilities within various lifeline systems (including highway-roadway transportation systems) (FEMA, 2002). It requires that users of HAZUS must own a copy of ArcView and understand its use.

It was decided not to adopt the Arc-View add-on approach for REDARS™ 2 for the following reasons:

- Not all (and possibly not even a majority of) prospective REDARS™ 2 users own ArcView.
- ArcView is robust software that requires training of prospective users, and also costs about $1,500 per seat to purchase.
- Some prospective REDARS™ 2 users are in organizations that prefer the use of other GIS packages, possibly to the exclusion of ArcView.
- As a software development platform, ArcView is a moving target. ArcView 2, ArcView 3, ArcGIS/ArcView 8, and ArcGIS/ArcView 9 are currently in use by many organizations, and each is a subtly or substantially different programming environment.

Instead, it was decided that REDARS™ 2 would have internal license-free GIS capability using Encompass Active-X components provided by Geodesy (a member of the RDT). These components require little if any user experience with GIS, yet provide an appropriate depth of GIS capability. Since Caltrans has no particular GIS standard, use of built-in, license-free GIS software was acceptable to the Caltrans project staff.

It is noted that REDARS™ 2 could use third-party GIS component sets like ESRI's MapObjects or ArcObjects in place of Geodesy's Encompass components, with little or no additional development effort. However, these component sets would provide little if any additional functionality to the user, and would require the user to purchase a license.

3.2.3 <u>Software Dependencies</u>

Given these platform decisions, REDARS™ 2 has no external software dependencies or licensing costs beyond the Windows operating system itself. The user need not own Visual Basic, Microsoft Access, or GIS software in order to install and run REDARS™ 2. However, sophisticated users who wish to view or edit REDARS™ 2 data or meta-data in detail need to own a copy of Microsoft Access. It is noted that, although Access is not a Caltrans standard, all of the members of the Caltrans project staff who have worked with REDARS™ 2 under this project have Microsoft Access software and understand its use.

3.2.4 <u>Augmentable and Replaceable Code</u>

The SRA portions of REDARS™ 2 have been programmed in augmentable and replaceable modules in dynamic link libraries (DLLs). This design of REDARS™ 2 facilitates the addition of new and improved models/modules for estimation of seismic hazards, component performance, and system performance, as they are developed from future research and engineering studies. These new models/modules can be programmed in any language that compiles to ActiveX, such as Visual Basic (VB) and Visual C++. The new models/modules will be selectable for use in REDARS™ 2 without modification to the REDARS™ 2 core program.

3.3 REDARS™ 2 INPUT

An important element of the REDARS™ 2 usability planning was the simplification of the input data development process to the extent possible. Toward this end, an Import Wizard was developed to enable users to readily access federally available data bases. In addition, other input data have been identified that cannot be developed through the Import Wizard and therefore must be provided by the user.

3.3.1 <u>Import Wizard</u>

The development of input data for REDARS SRA applications requires the use of several publicly-available databases, including: (a) the National Highway Performance Network (NHPN) database for defining network topology only (spatial coordinates); (b) the Highway Performance Monitoring System (HPMS) database for defining highway network attributes only (e.g., number of lanes, functional class, etc.); (c) the National Bridge Inventory (NBI) database which defines certain bridge attributes; and (d) regional databases for defining O-D zones and associated trip tables, NEHRP soil conditions, etc. Unfortunately, the information contained in these various databases is not always compatible. For example, the segmentation of the links in the NHPN database (network topology) is not always consistent with that of the HPMS database (link attributes). In addition, bridge coordinates from the NBI database are not always consistent with the roadway link locations given in the NHPN database. The resolution of these issues in order to develop consistent input data for a REDARS SRA application can be time consuming.

To reduce these user time requirements, a REDARS™ 2 Import Wizard has been developed. This Wizard guides the user through each step of the input-data development process, and automates the resolution of many of the above inconsistencies. It consists of a series of prototype user interfaces (graphical user interfaces and dialogue windows) that are successively activated by users to guide them through each step of the development of the input data. Such interfaces enable users to locate publicly available databases within the Wizard, define study region boundaries, establish the various network, soil, and bridge input databases within REDARS, define boundary conditions (e.g., trip demands on the highway network from outside of the study region), and check network-model connectivity and continuity of O-D zones (Figure. 3-1). The Import Wizard is further described in Appendix B and in Cho et al. (2006a).

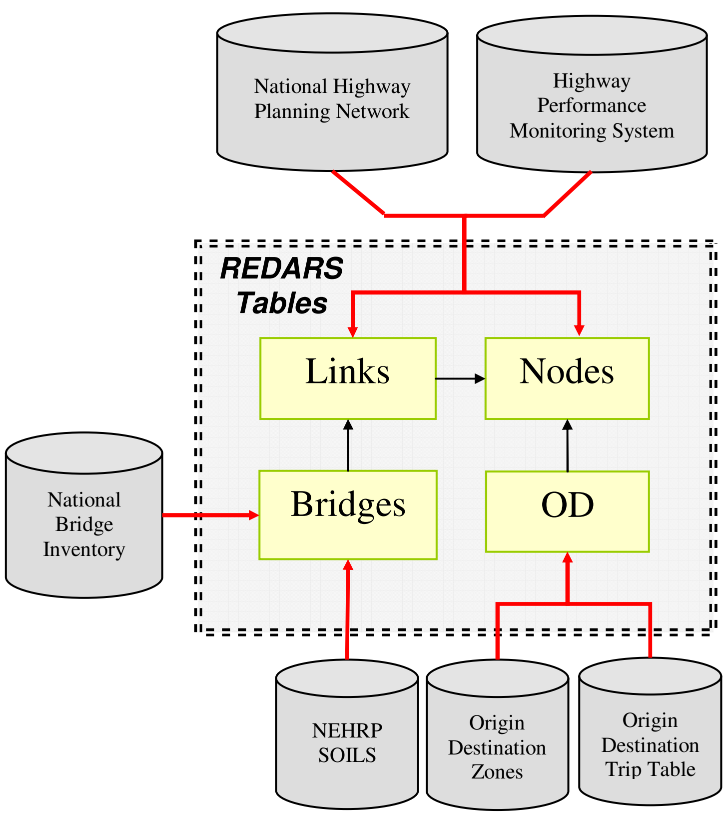


Figure 3-1. REDARS™ 2 Import Wizard

3.3.2 <u>User-Provided Input Data</u>

In addition to the data accessed from publicly-available data bases through the Import Wizard, additional data that are not available from such data bases will usually also be needed. These input data, which are listed below, are provided by the user.[1]

- *Input Data for Import Wizard.* The user must contact the MPO for the region is order to obtain data describing centroidal locations of all origin-destination (O-D) zones, together with trip tables that define the number of trips from each zone to each of the other zones in the region. In addition, if NEHRP soils data are available for the region, these data must be provided as input to the Import Wizard.

- *Earthquake Data.* For each earthquake to be considered in the SRA, the user must specify the magnitude, location, and source attributes (causative fault attributes for each fault-based earthquake or areal zone locations for each zone-based earthquake). If the SRA is to be probabilistic, an earthquake walkthrough table must be provided. Note that the RDT has developed a walkthrough table that can be directly used by Caltrans for SRA of any highway-roadway system in the state. The development of this earthquake walkthrough table is described in Section 4.2 of Chapter 4.

- *Ground Motions.* The user must select one of the site-specific ground-motion models currently contained in REDARS™ 2 to estimate ground shaking hazards throughout the highway-roadway system. Alternatively, the user has an option to use ShakeMap estimates of: (a) ground motions from one of the prior actual earthquakes or hypothetical earthquake scenarios included in the REDARS™ 2 database; or (b) ground motion estimates obtained in real time after an actual earthquake.

- *Liquefiable Site Data.* The user must identify any potentially liquefiable sites within the highway-roadway system, and provide soils data for these sites that are needed to estimate site-specific liquefaction hazards during each scenario earthquake and simulation. Use of these data to estimate site-specific liquefaction hazards throughout the highway-roadway system is summarized in Section 4.4 of Chapter 4.

- *Bridge Data.* For bridges, the user must provide the following input data: (a) each bridge that crosses over another roadway must be identified, along with the link number of the underlying roadway; and (b) each bridge that has been retrofitted by column jacketing must be identified. Note that REDARS™ 2 provides default retrofit enhancement factors that can be overridden by the user (Shinozuka, 2004).

- *Analysis Options.* The user must specify if the analysis is to be deterministic or probabilistic.

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[1] If the user cannot provide these additional input data, REDARS™ 2 assumes default values of these data, and an "out-of-the-box" baseline SRA can be carried out on this basis for whatever earthquakes are specified by the user. Of course, if improved values of these input data can be provided by the user, the results of the SRA will be more reliable and meaningful.

- *User-Specified Models.* If a user wishes to override the default damage-state model or repair model for any component, he/she must provide a user-specified model for that component.

- *Monitored Elements.* If the SRA is to be probabilistic, REDARS™ 2 enables users to specify: (a) any components within the highway-roadway network for which it is desired to monitor seismic hazard and/or component damage probabilities; (b) any origin-destination zones for which it is desired to monitor post-earthquake access or egress times and/or trip production or attraction; and (c) any key routes in the system for which it is desired to monitor post-earthquake travel times.

- *Override of Default Input Data.* Any of the default input model parameters contained in REDARS™ 2 can be overridden by the user.

3.4 REDARS™ 2 OUTPUT

3.4.1 Decision Issues

Discussions with Caltrans staff for this project as well as prior discussions with Caltrans staff during prior projects (e.g. Werner, Ostrom, and Taylor, 2002) have indicated the following decision issues that may be guided by REDARS™ 2 output: (a) identification of potentially vulnerable bridges, particularly along lifeline routes; (b) assessment of alternative detour routes and other traffic management strategies in reducing post-earthquake traffic congestion; (c) management of post-earthquake repair resources; (d) the current potential for significant losses due to earthquake damage to California highway-roadway systems, and how alternative component or system improvement options might reduce these risks.

3.4.2 Output Types

To enable Caltrans and other users to address these decision issues, REDARS™ 2 has been designed to provide SRA results in terms of any or all of the following parameters:

- *Economic Losses.* REDARS™ 2 provides estimates of economic losses due to travel time delays and trips not taken that result from earthquake-induced damage to and congestion of the highway-roadway system. Estimates of post-earthquake costs to repair damaged components are also provided.

- *Increased Travel Times to/from Any User-Selected Locations at Various Post-Earthquake Times.* These locations may include hospitals, airports, emergency-response centers, centers of commerce, etc.

- *Reduced Trips to/from Any User-Selected Location(s) at Various Post-Earthquake Times.* Reductions in trips to/from a given center of commerce can provide a first-order measure of higher-order economic impacts of earthquake damage to the highway-roadway system; i.e., reduced trips could mean fewer customers, reduced availability of supplies or materials essential to the operations of a business, etc.

- *Increased Travel Times along Any User-Selected Route(s) at Various Post-Earthquake Times*. Caltrans has designated various routes throughout the state as lifeline routes that must be capable of accommodating emergency-response vehicles immediately after an earthquake. Post-earthquake travel-time results for such routes can indicate their ability to meet this objective.

- *Component Damage States.* REDARS™ 2 provides damage-state results for individual bridges and other components, or in terms of maps of component damage states throughout the entire highway-roadway system.

- *Seismic Hazards.* REDARS™ 2 can provide site-specific ground motions as well as permanent ground displacements due to liquefaction or surface fault rupture at any component site throughout the highway-roadway system.

The above results can be obtained from deterministic or probabilistic SRAs in a tabular form, graphical form, or (except for economic losses) as maps showing distributions of these losses throughout the highway-roadway system. Section 2.5 of Chapter 2 further discusses how these various results may be used to guide Caltrans' seismic-risk-reduction decision making.

CHAPTER 4
TASK 2: UPDATED HAZARDS MODULE FOR CALIFORNIA APPLICATIONS

4.1 OBJECTIVE

Under Task 2, the REDARS™ Development Team (RDT) collaborated with Caltrans during their evaluation and selection of models for estimating earthquake occurrences and seismic hazards due to ground motion, liquefaction, and surface fault rupture. The RDT also programmed the models, and developed interfaces to enable them to be included into the REDARS™ Hazards Module.

4.2 SUBTASK 2.1: CALIFORNIA EARTHQUAKE MODELING

4.2.1 Overview

In a SRA of any spatially-dispersed lifeline system, separate scenarios are needed to evaluate the simultaneous effects (including systemic consequences of damage) of individual earthquakes on components at diverse locations. In this, regional earthquake models are used to develop a table of earthquake occurrences over time, in which each earthquake: (a) is represented as an earthquake magnitude and location, whose occurrences over time represent the model's estimated of frequency of occurrence of earthquakes with that magnitude; and (b) can be associated with a random areal source or a causative fault. This table of earthquake occurrences -- termed a walkthrough table -- also contains the attributes of the causative fault for each fault-based earthquake, in order to facilitate subsequent computation of various measures of source-site distance that accommodate a variety of different ground motion models in REDARS™ 2).

Under Subtask 2.1, the RDT has developed a Coastal California earthquake walkthrough table for use in Caltrans' future REDARS™ 2 applications to highway-roadway systems statewide. The development of this walkthrough table is briefly summarized below, and is further described in Appendix B of Werner et al. (2006).

4.2.2 Regional Earthquake Source Models

The Coastal California walkthrough table is based on regional earthquake source models that were adapted from models used by the United States Geological Survey during their development of national seismic-hazard maps (Frankel et al., 2002). These models incorporate: (a) smoothed historical seismicity as a 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) geologic slip rates to estimate earthquake recurrence times for faults in California. Their application to development of the Coastal California walkthrough table also uses data from the California Geologic Survey, the Northern California Earthquake Data Center, and the Southern California Earthquake Center.

Earthquake walkthrough tables are developed externally, for use as input to the REDARS™ 2 software. Therefore, the tables can be updated in the future to accommodate new advances in earthquake source modeling, without modifying the software.

4.2.3 <u>Walkthrough Table Development Process</u>

The following paragraphs summarize process followed to develop an earthquake walkthrough table for use as input to REDARS™ 2 probabilistic SRA applications.

4.2.3.1 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.

4.2.3.2 Step 2. Scenario Earthquakes during Each Year of Walkthrough

Under Step 2 the earthquake walkthrough table with the above duration is generated. This is done first for Year 1, and then for each succeeding year of the walkthrough. For each year, this process generates a series of uniform random numbers that are used with various earthquake probability distributions developed from the regional earthquake model and data summarized in Section 4.2.2, 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 walkthrough process allows for the possibility that more than one potentially damaging earthquake can occur during a single year.

4 2.4 <u>Coastal California Walkthrough Table</u>

The Coastal California earthquake walkthrough table has a duration of 10,000 years, and includes 28,640 earthquakes throughout the state whose moment magnitudes range from 5.0 to 7.9. These include earthquakes generated by rupture along known faults with known attributes, as well as random-areal earthquakes on unknown faults whose attributes are estimated randomly. Table 4-1 lists the earthquake and fault attribute data that are provided for each earthquake occurring during each year of the walkthrough table. Figure 4-1 displays the locations of all of the earthquakes in the table, as subdivided according to moment-magnitude range.

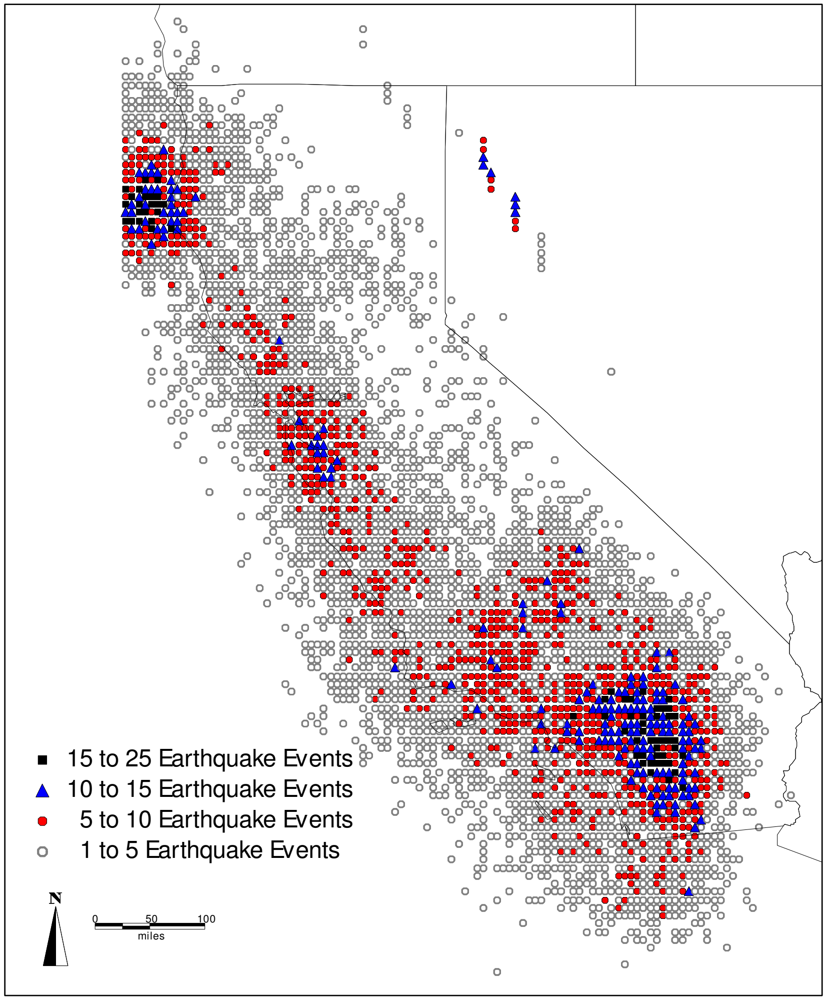
All scenario earthquakes in the walkthrough table are assumed at this time to be generated by one single fault-rupture segment. Future extensions of REDARS™ will enable rupture along multiple fault segments to be considered.

4.2.5 <u>Other Earthquake Representations in REDARS™ 2</u>

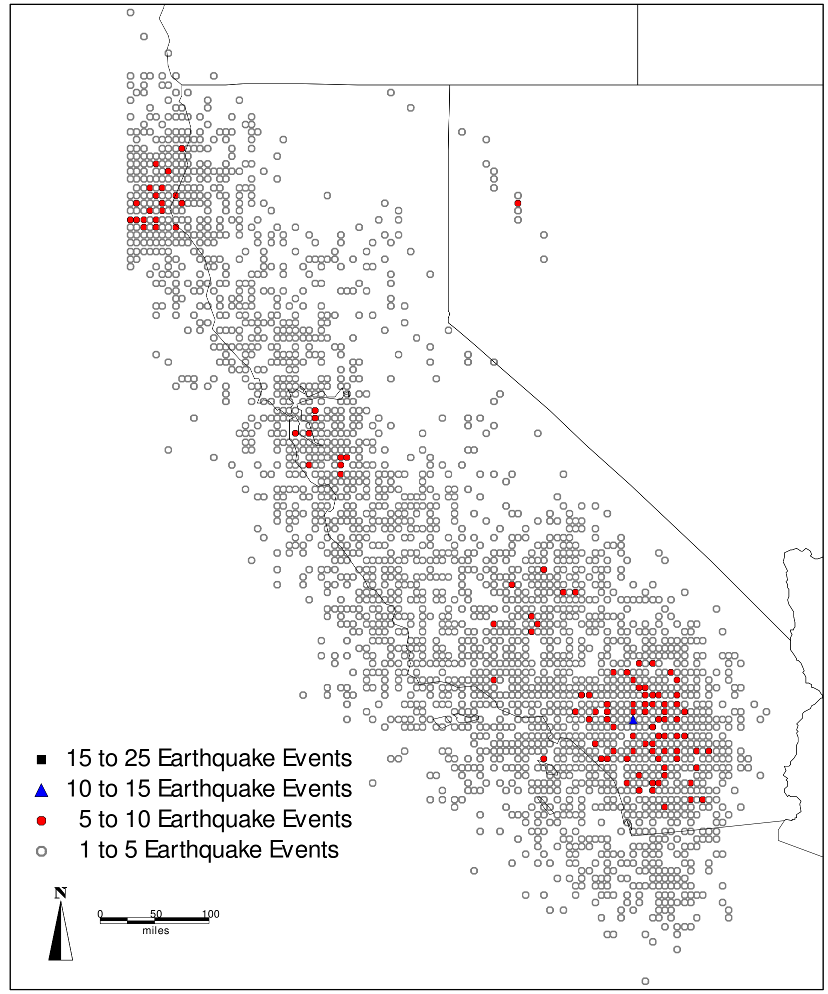
The Coastal California earthquake walkthrough table will be used in probabilistic applications of REDARS™ 2 to represent effects of uncertainties in earthquake occurrence, magnitude, and location. For deterministic applications of REDARS™ 2, the user may define the earthquake event by either: (a) selecting any earthquake in the walkthrough table; (b) considering hypothetical or actual earthquake events for which ShakeMap ground motion estimates have been developed; or (c) by specifying any arbitrary earthquake magnitude and location.

Table 4-1. Data Contained in Walkthrough Files as shown by a Portion of the File developed for REDARS™ 2 SRA of Los Angeles Testbed Roadway System (see Appendix D)

Fault/ Earthquake Data		Walkthrough Year			
Type	Description/Units	73	75	76	77
EQ Number during Year	Can be 0, 1, 2 or more.	1	1	1	1
Moment Magnitude	--	5.2	7.4	7.2	6.8
Fault Style	Integer from 1-4 (1 = strike-slip fault, 2 = reverse fault, 3 = normal fault, 4 = other (e.g., reverse oblique)	1	1	2	2
Fault Number	Random sources are numbered "0".	0	137	156	108
Fault Name	--	random	San Andreas	Sierra Madre	Oak-Ridge
No. of End-End Segments defining Fault Rupture	One segment now used for coastal CA faults. Multi-segment model for New-Madrid fault in CUS.	1	1	1	1
Fault-Rupture Plane End-Point Latitudes, Longitudes	End Point 1 along Top of Fault Plane, deg.	34.795, -119.515	34.310, -117.530	34.280, -118.290	34.170, -119.656
	End Point 2 along Top of Fault Plane, deg.	34.805, -119.484	33.350 -115.710	34.197 -117.707	34.140, -119.357
	End Point A along Base of Fault Plane, deg.	34.795, -119.515	34.310, -117.530	34.357, -118.257	34.092, -119.656
	End Point B along Base of Fault Plane, deg.	34.805, -119.484	33.350 -115.710	34.197 -117.707	34.092, -119.357
Fault Plane Orientation	Dip Angle, deg.	90	90	45	30
	Azimuth of Dipping Plane of Fault, deg.	0	0	0	180
EQ Hypocenter Depth	km.	14.72	8.99	9.04	4.99
Total Width of Fault Plane	m.	9.96	4.73	9.40	7.90
EQ Epicenter Coordinates	Latitude and Longitude, deg.	34.800, -119.500	33.792, -116.549	34.295, -118.045	34.092, -119.509
EQ Seismogenic Zone	Depth to Rupture Plane, km. (assumed to be 3 km)	4.757	4.256	3.0	3.0
EQ Center-of-Energy-Release	Depth from ground surface, km	11.017	6.507	8.78	4.96
	Latitude and Longitude, deg.	34.801, -119.496	33.754, -116.477	34.245, -117.967	34.131, -119.646
Fault Plane Widths on Either Side of Fault Plane	Integer named ZD (=1 if user-specified input fault widths are provided; =2 if default values are used)	0	0	0	0
Zone of Deformation Widths (to left and to right of main trace of fault rupture)	Units of m; Ignored if ZD = 0	--	--	--	--

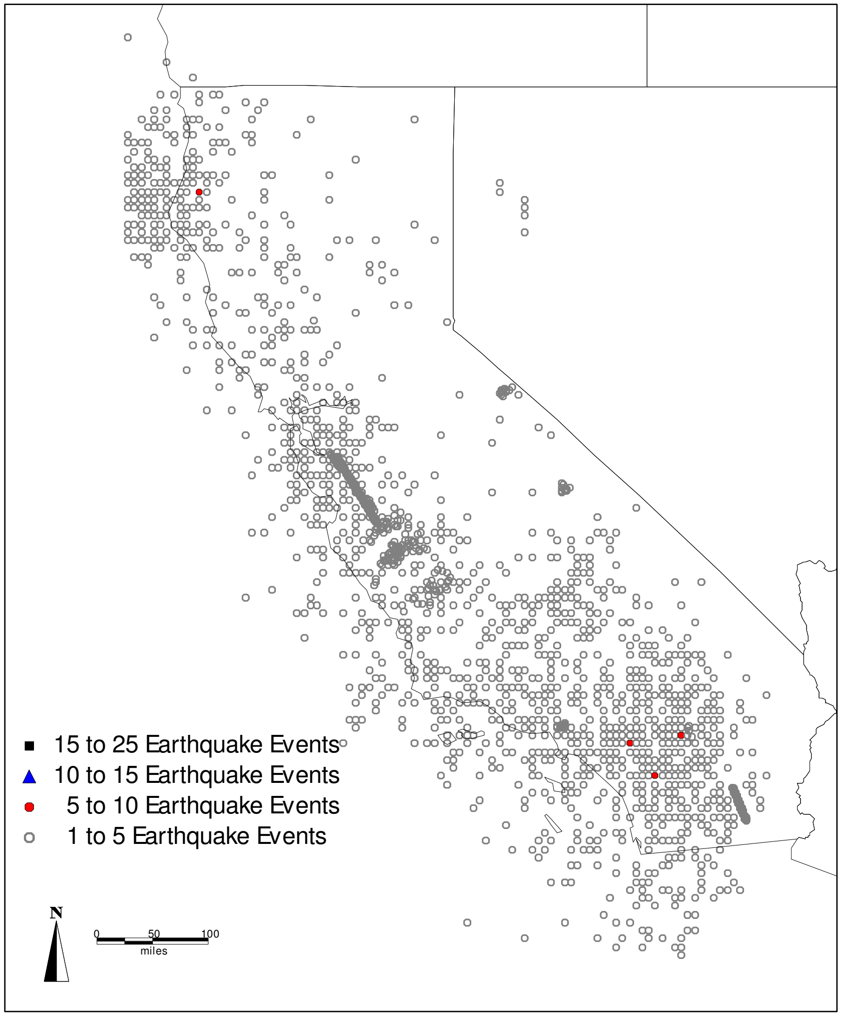


a) 5.0 ≤M_w < 5.5 (14,704 Earthquakes)

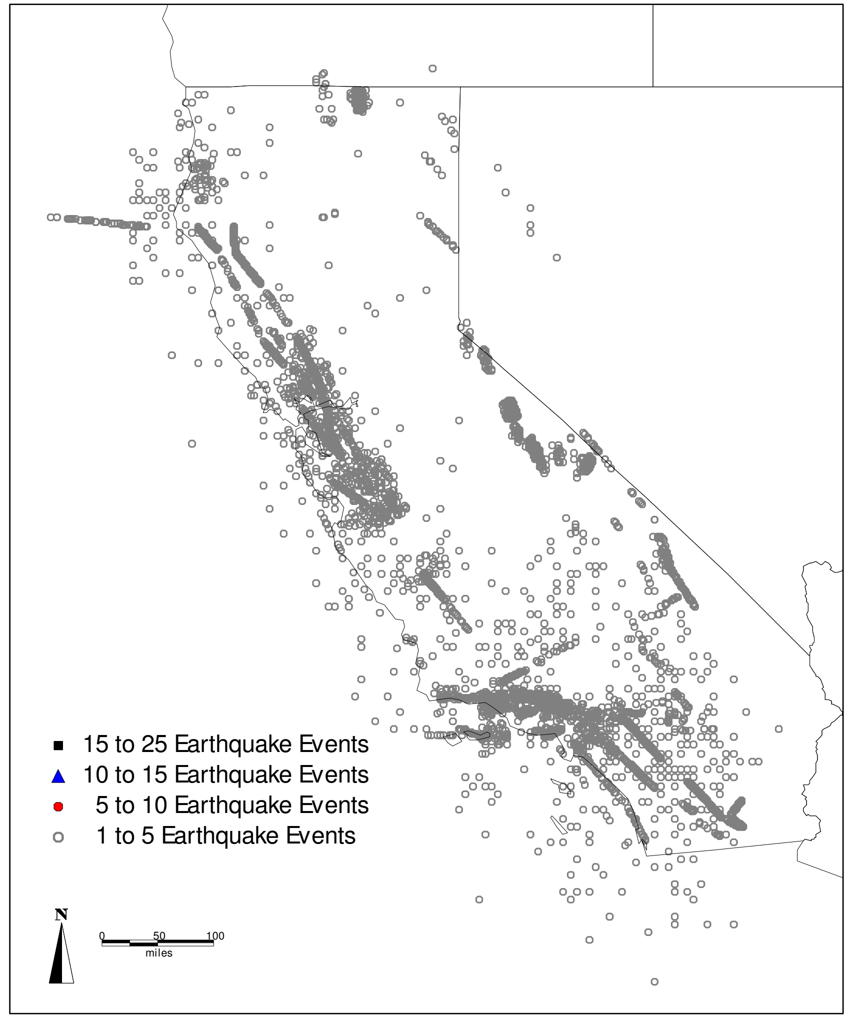


b) 5.5 ≤M_w < 6.0 (4,371 Earthquakes)

Figure 4-1. Magnitudes and Epicenter Locations for Earthquakes in Coastal California Walkthrough Table (page 1 of 3)

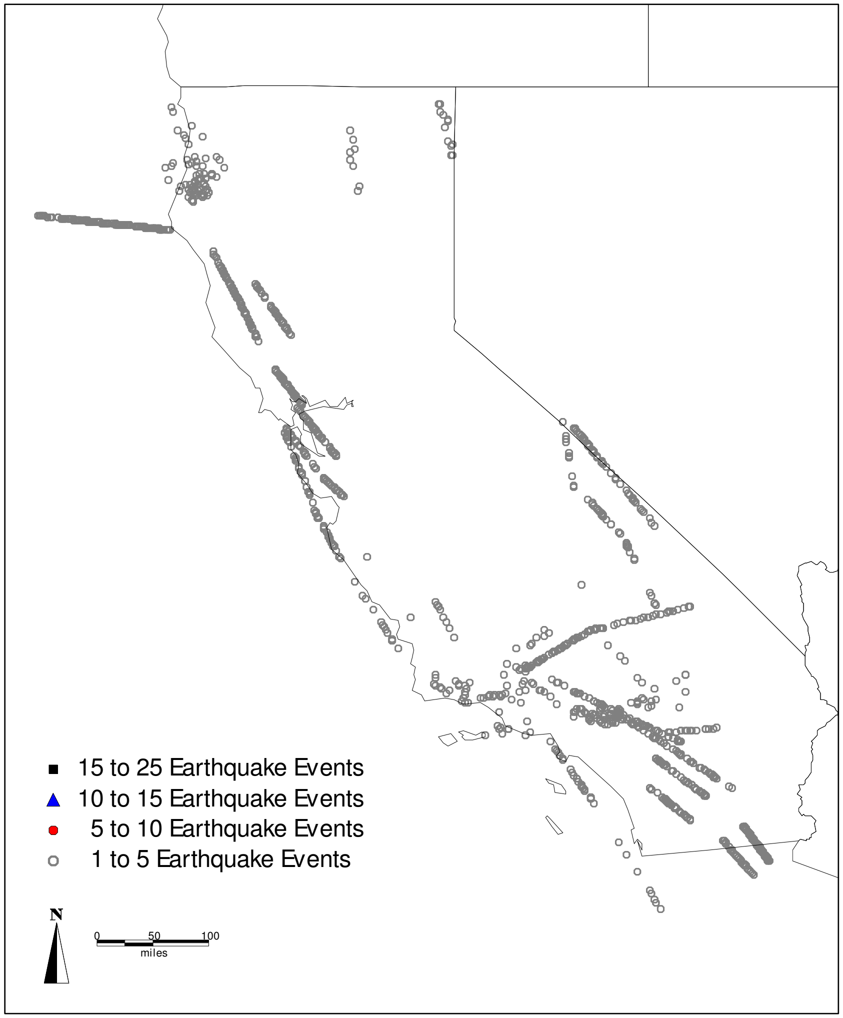


c) $6.0 \leq M_w < 6.5$ (2,691 Earthquakes)

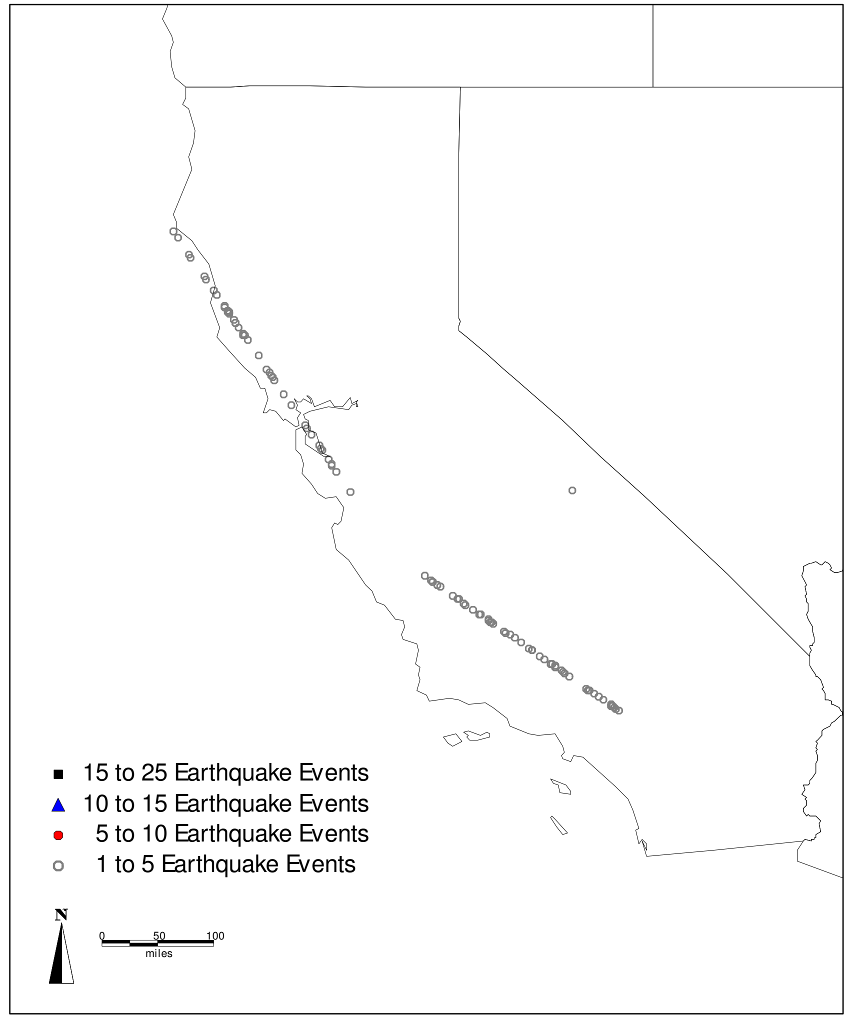


d) $6.5 \leq M_w < 7.0$ (5,408 Earthquakes)

Figure 4-1. Magnitudes and Epicenter Locations for Earthquakes in Coastal California Walkthrough Table (page 2 of 3)



c) $7.0 \leq M_w < 7.5$ (1,371 Earthquakes)



d) $7.5 \leq M_w < 7.0$ (95 Earthquakes)

Figure 4-1. Magnitudes and Epicenter Locations for Earthquakes in Coastal California Walkthrough Table (page 3 of 3)

4.3 SUBTASK 2.2: GROUND MOTION HAZARDS

4.3.1 Overview

Past earthquakes have shown that roadway 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 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.

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 many earthquakes that will need to be considered in a probabilistic SRA of a highway-roadway system.

Ground motion attenuation models characterize the 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 as well. Terms for characterizing uncertainties in the ground motion predictions are also included in these equations. The various models that are available may use differing definitions of source-site distance. Therefore, since it is planned to eventually enable REDARS™ 2 to accommodate a library of multiple models for each of several earthquake-prone regions of the country, from which a user can select a preferred model for use in their particular SRA application. REDARS™ 2 must include a capability to compute the variety of source-site distance definitions that may be embodied in these multiple models.

Therefore, under Subtask 2.2, the RDT developed software for inclusion into the REDARS™ 2 Hazards Module that has the following features: (a) it computes source-site distances according to a wide range of different definitions so that, once a user selects a preferred ground motion model for use in their SRA, the appropriate distance definition can be used; and (b) for California applications, it uses the Abrahamson-Silva (1997) model to estimated site-specific ground motions. These developments are summarized below. It is noted that this software also computes additional fault-specific parameters that are needed to estimate hazards from surface-fault rupture (see Section 4.5).

4.3.2 Source-Site Distance Calculations

Table 4-2 and Figure 4-2 show the various source-site distance definitions and other parameters for ground-shaking and surface-fault-rupture hazards that are computed by REDARS™ 2. These computations account for the fault's orientation (azimuth) and direction of dip relative to the location of the site of each component in the roadway system. They also assume that rupture occurs along a single rectangular fault plane (i.e., rupture along multiple segments and trapezoidal fault planes are excluded). Finally, the computed source-site distances will depend on: (a) whether a normal can be drawn from the highway component's site to the ruptured fault; and (b) if such a normal can be drawn, and if the fault plane is dipping, whether the site is along the hanging wall or foot wall of the ruptured fault. As described in Appendix D of Werner et al. (2006), the walkthrough tables contain all of the input parameters needed for these source-site distance calculations which include the ruptured fault's location, orientation, type, and extent of rupture, as well as parameters that characterize the points of initiation of rupture (see Figs 4-3 to 4-7).

4.3.3 Ground Motion Model

4.3.3.1 Background

REDARS™ 2 uses ground motion attenuation models to estimate ground motions at each component site due to each earthquake in the walkthrough table. These models take the form of an equation with terms that 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 characterizing uncertainties in the ground motion predictions are also included.

Future versions of REDARS™ will contain a library of different ground motion models for various regions of the United States, and that users of REDARS™ will be able to select any one of these models (or a weighted average of multiple models) for use in their particular SRA. For California applications, several current models have been available for estimation of site-specific ground motions due to shallow crustal earthquakes in active tectonic regions of the United States are available and widely used in current engineering practice (e.g., see the January/February 1997 edition of Seismological Research Letters for a description of several such models). Section 4.3.3.4 describes plans for including updated ground-motion models in the future.

At this time, one of these current models has been included in REDARS™ 2 for SRA of highway systems in California -- the Abrahamson-Silva (1997) model for shallow crustal earthquakes within the western United States. The implementation of this model in REDARS™ 2 is summarized in Section 4.3.3.3, and is further described in Appendix D of Werner et al. (2006).

Table 4-2.
Parameters Obtained from REDARS™ 2 Source-Site Distance Calculations

Use in REDARS™ 2	Parameter
Site-Specific Ground Motions (Fig. 4-2)	Epicentral distance (DEPI)
	Hypocentral distance (DHYPO)
	Distance to center of energy release (DCERL)
	Minimum distance to seismogenic zone (DSEIS)
	Minimum distance to fault rupture (SDRP)
	Minimum distance to surface projection of fault rupture plane (SDPRP)
	Minimum distance from site to ruptured fault segment at ground surface (DSRUP)
Other Parameters for Ground Motion Models that include Directivity Effects	For strike-slip faults: (a) predominant direction of strong ground motion relative to site (Fig. 4-3); and (b) angle THETA (Fig. 4-4).
	For dipping faults: (a) predominant direction of ground motions relative to footwall and hanging wall and to site (Fig. 4-5); (b) angle PHI (Fig. 4-6) and (c) whether site is subjected to directivity adjustments (Fig. 4-7).
	Predominant direction of ground motions: estimated from location of epicenter along ruptured fault. Assumed to be toward end of fault that is furthest from epicenter.
Site-Specific Ground Motions or Fault Rupture Displacement	Whether site is on hanging wall or footwall of normal or reverse fault. Computed only if NORMAL = 1.
Fault Rupture Displacement	Whether line can be drawn from site that is normal to ruptured segment of fault. If so, NORMAL = 1; otherwise NORMAL = 0
	Ratio of minimum distance of intersection of NORMAL with fault line to length of fault plane. Computed only if NORMAL =1.

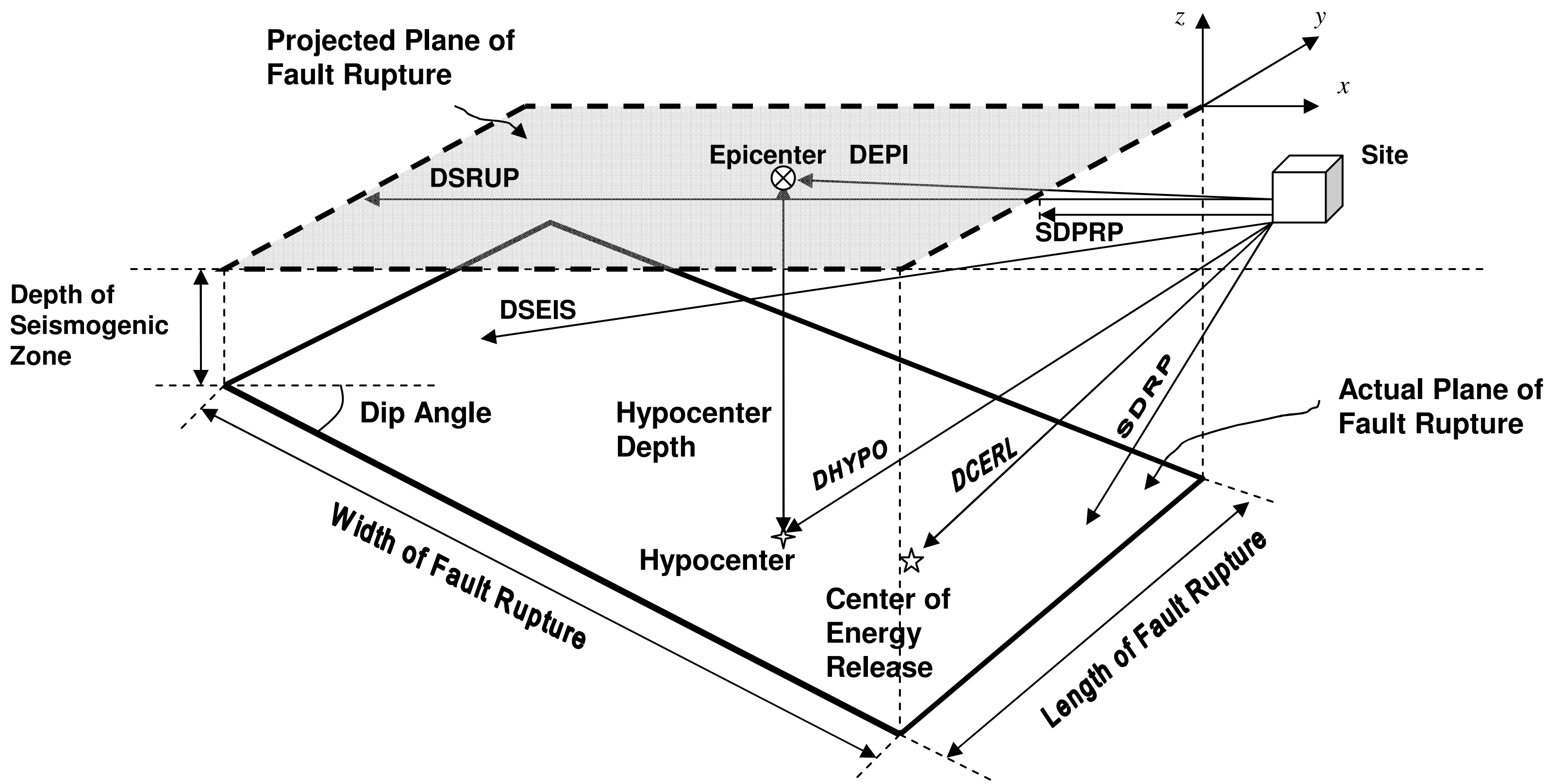


Figure 4-2. Source-Site Distances computed in REDARS™ 2

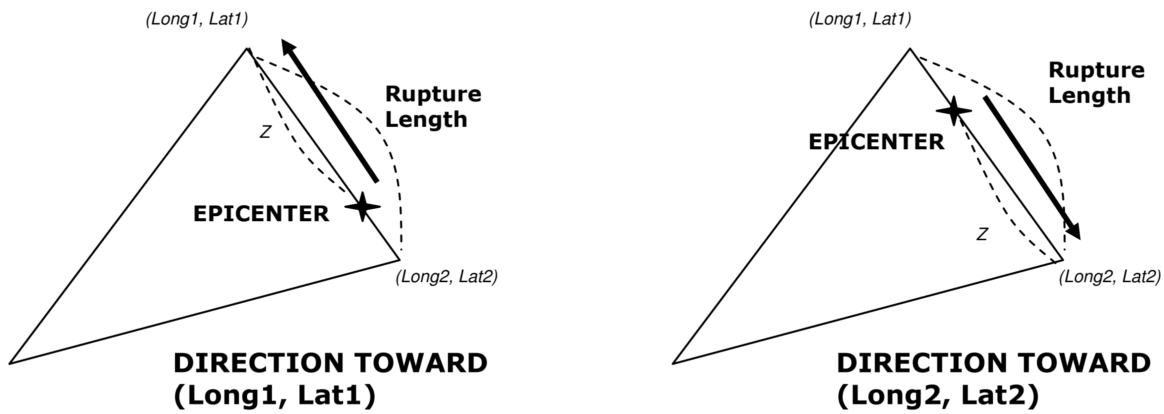


Figure 4-3. Direction of Rupture Propagation for Strike-Slip Faults

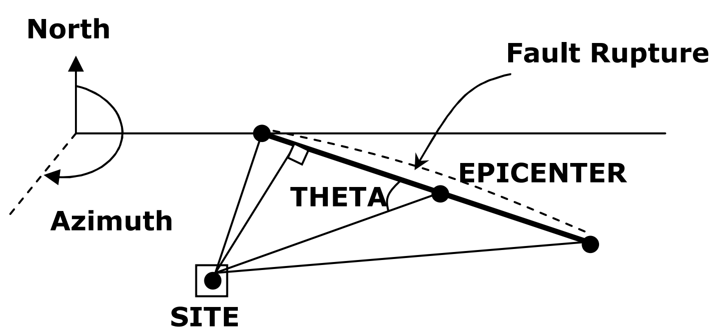
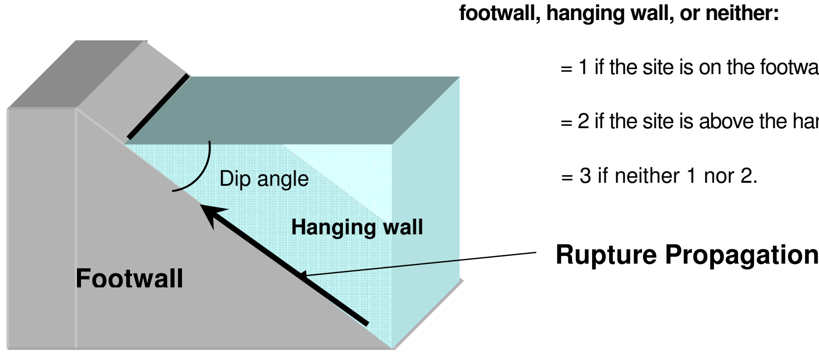


Figure 4-4. Plan View of Any Fault Illustrating "Theta"



FOOTWALL: Indicator variable for position of site on footwall, hanging wall, or neither:

= 1 if the site is on the footwall,

= 2 if the site is above the hanging wall,

= 3 if neither 1 nor 2.

Figure 4-5. Assumed Direction of Rupture Propagation for Dipping Faults (Reverse, Reverse/Oblique)

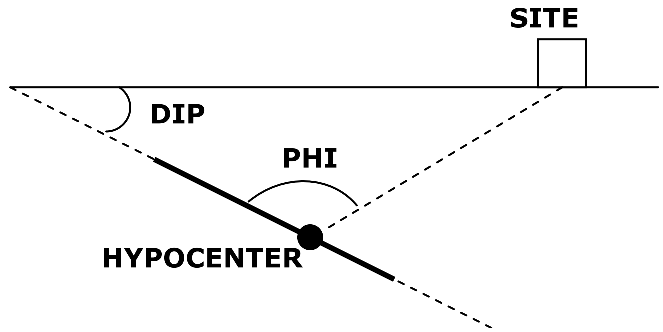


Figure 4-6. Section View of Dipping Fault Illustrating Phi

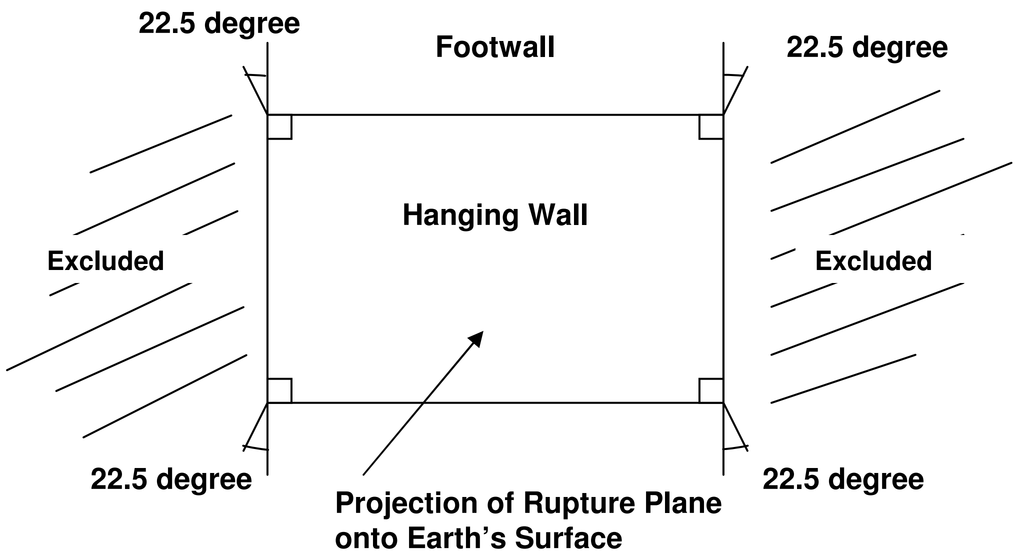


Figure 4-7. Plan View of Projection of Fault Plane and Regions Excluded from Directivity Effects

4.3.3.2 Model Output

Results from ground-motion attenuation models consist of spectral accelerations for a wide range of natural periods (including the zero-period spectral acceleration which is equal to the peak ground 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 current 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 other spectral accelerations can also readily be saved from the ground-motion attenuation model results, with only minor adjustments to the REDARS™ 2 software.

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 these 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.

4.3.3.3 Abrahamson-Silva (1997) Model

The Abrahamson-Silva (1997) ground-motion attenuation model that is to be used in Caltrans' applications of REDARS™ 2 statewide has the following features:

- It estimates spectral accelerations caused by shallow crustal earthquakes in active tectonic regions of the Western United States, excluding subduction earthquakes.

- It has the following mathematical form:

$$\ln S_a(g)_i = f_1(M_w, r_{rup})_i + Ff_3(M_w) + HWf_4(M_w, r_{rup})_i + Sf_5(\overline{pga}_{rock})_i + \varepsilon_{inter}(M_w) + (\varepsilon_{intra})_i \tag{4-1}$$

  where the subscript *i* denotes those terms that, for each earthquake, are computed separately for each component site (where *i* is the component number). Those quantities without the subscript *i* are computed once for each earthquake only. The term $f_1(M_w, r_{rup})_i$ is the basic functional form of the attenuation model for rock sites and strike slip faulting. The terms $Ff_3(M_w)$, $HWf_4(M_w, r_{rup})_i$, and $Sf_5(\overline{pga}_{rock})_i$ represent modifications to this basic form to account for effects of other types of faulting, hanging wall effects, and local soil conditions. The quantities $\varepsilon_{inter}(M_w)$ and $(\varepsilon_{intra})_i$ represent effects of inter-event uncertainties (earthquake-dependent only) and intra-event uncertainties (earthquake- and component-dependent).

- The above functionality is represented through a series of numerical coefficients that are used to compute each term in Equation 4-1, and to thereby enable the model to calculate both horizontal and vertical components of spectral acceleration. Since the current component damage state models in REDARS™ 2 use horizontal ground motions only, the coefficients for computing vertical accelerations are excluded from this adaptation of the Abrahamson-Silva (1997) model. However, if future component models are added into REDARS™ that require vertical as well as horizontal input ground motions, the Abrahamson-Silva coefficients for computing vertical motions can be readily added.

- The Abrahamson-Silva model actually provides these coefficients for 28 periods ranging from 0.01 sec. to 5.0 sec. However, since the current bridge models in REDARS™ 2 only consider periods of 0.3 sec. and 1.0 sec., and since current REDARS™ 2 liquefaction models consider peak ground acceleration only (i.e., spectral accelerations for a period = 0.0 sec.), this REDARS™ 2 adaptation of the Abrahamson-Silva model includes coefficients for those periods only. However, if future component or liquefaction models in REDARS™ consider other periods, coefficients for these periods can be readily added.

- This model uses moment magnitude (M_w) to represent earthquake magnitude, and defines the source-site distance (r_{rup}) as the closest distance from the site to the rupture plane. In this, if the fault plane is vertical or is dipping away from the site, r_{rup} will be the distance from the site to the fault-rupture location on the ground surface (and will be straightforward to calculate.) However, if the fault plane is dipping toward the site, r_{rup} will depend on the dip angle and will be more complicated to compute.

- This ground motion model considers two site classifications: a rock site (with a soil thickness < 20m that overlies rock) and a deep soil site (with soils whose thickness exceeds 20 m).

- The model 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 in ground motion on hanging wall and foot wall of a dipping fault.

- Abrahamson and Silva define the horizontal spectral acceleration as representing the average (and not the upper bound) of the two components of horizontal motion recorded during the various earthquake events cited in their paper.

As noted earlier, the step-by-step procedure used to implement the Abrahamson-Silva (1997) model in REDARS™ 2 is described in Appendix D of Werner et al. (2006).

4.3.3.4 Future Inclusion of Updated Ground Motion Models

The next update of the California ground-motion models for application of REDARS™ will incorporate new attenuation relationships that have been developed under the "Next Generation of Ground Motion Attenuation Models" (NGA) project. This comprehensive and interactive research project was conducted jointly be the Pacific Earthquake Engineering Research Center Lifelines Program (PEER-LL), the United States Geological Survey (USGS), and the Southern California Earthquake Center (SCEC). Under this project, five sets of updated attenuation models have been developed by teams of recognized engineering-seismology experts. This model development has been supported by other project components that include: (a) development of an updated and expanded database of recorded ground motions; (b) supporting research project to provide constraints on the selected functional form of the attenuation relationships; and (c) a program of interactions throughout the model development process that has provided input and reviews from the scientific-research and engineering-user communities (Abrahamson et al., 2006).

In the next extension of REDARS™, each of the five sets of NGA models will be programmed and incorporated into the REDARS™ Hazards Module. The REDARS™ user will be able to select any one of these models for use in his/her SRA application. This will provide the following benefits: (a) the latest state-of-knowledge models for estimation of ground motions throughout California will be incorporated; and (b) REDARS™ 2 users will have the capability of carrying out parametric analyses to assess the sensitivity of the SRA results to the variations in ground-motion predictions among the various models.

4.4 SUBTASK 2.3: LIQUEFACTION HAZARDS

4.4.1 Overview

Liquefaction 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 stiffness and shear strength of the soil 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) that are in contact with the liquefied soils, and a loss of frictional resistance of pile elements at their interface with liquefied soil layers. If these effects are sufficiently large, they can damage highway structures.

Under Subtask 2.3, the RDT collaborated with members of Caltrans geotechnical engineering staff to review existing models for estimating liquefaction hazards and select a preferred model for inclusion into REDARS™ 2. The selection of the preferred model was based on two criteria. First, the procedure was to be technically sound and based on well established liquefaction hazard evaluation procedures. The second criterion considered the practicality of the procedure for REDARS™ 2 SRA applications, which will often involve a large number of sites throughout a spatially dispersed roadway system at which liquefaction hazards would need to be estimated. Furthermore, in the absence of digital databases of soil properties needed to evaluate liquefaction hazards, it will be necessary for the REDARS™ 2 user to compile this material. Therefore, to reduce the potentially significant effort that could be required to compile data for large numbers of soil input parameters for each of these many sites, selection of a technically sound model that used fewer soil parameters was an important consideration in this model selection process.

4.4.2 Liquefaction Model

Based on the above considerations, the procedure selected for implementation with REDARS™ 2 consisted of the following steps: (1) the user's initial screening of soil sites throughout the roadway system, to identify those sites that are potentially liquefiable sites; (2) estimation of liquefaction-induced lateral spread displacements at these sites; and (3) estimation of liquefaction-induced vertical settlements at these sites. This procedure is summarized below, and is further described in Appendix E of Werner et al. (2006).

4.4.2.1 Step 1. Initial Screening

Step 1 consists of initial screening of soil sites throughout the roadway 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 locations, and site topography, as described in Section E.3 of Werner et al. (2006). In REDARS™ 2, liquefaction hazards are computed only at those sites within the roadway system that are identified as being potentially liquefiable in this initial screening step.

4.4.2.2 Step 2. Lateral Spread Displacement Hazards

In Step 2, the Bardet et al. (2002) four-parameter model is used to estimate lateral spread displacements at each potentially liquefiable site in the roadway network. 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.

4.4.2.2.1 Input Data

Input data to the Bardet et al. models consists of

- *Earthquake-Dependent Data,* which are the moment magnitude of the earthquake (M_w) and the horizontal distance from the site to the earthquake's center of energy release (R).

.

- *Site Topography Data*, which are either the ground slope (S) or, for sites with a free face, the free face ratio which is ratio of the height of the free face to the distance from the face to the site (W), as defined in Equation 4-2 and illustrated in Figure 4-8.

$$S = \frac{1}{X} * 100{,}0 \qquad \text{and} \qquad W = \frac{H}{L} * 100.0 \qquad (4\text{-}2)$$

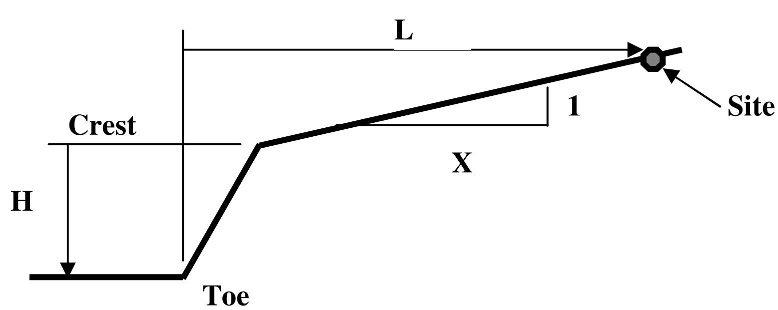


Figure 4-8. Definition of Slope, *S*, and Free-Face Ratio, W

- *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 blowcount is less than 15.

4.4.2.2.2 Median Value of Lateral Spread Displacement

When these input data have been compiled, the Bardet et al. four-parameter model computes the median value of the natural logarithm of the lateral spread displacement, according to the following equations:

For ground-slope conditions:

$$\log_{10}(D_H + 0.01) = -6.815 + 1.017M_w - 0.278\log_{10} R - 0.026R + 0.454\log_{10} S + 0.558\log_{10} T_{15} \tag{4-2}$$

For free-face conditions:

$$\log_{10}(D_H + 0.01) = -7.280 + 1.017M_w - 0.278\log_{10} R - 0.026R + 0.497\log_{10} W + 0.558\log_{10} T_{15} \tag{4-3}$$

where D_H is the lateral-spread soil displacement in units of meters, R is the distance from the earthquake source to the site in units of km, and the remaining terms in Equations 4-2 and 4-3 are defined in Section 4.4.2.2.1

4.4.2.2.3 Treatment of Uncertainty

The Bardet et al. model includes effects of uncertainties by computing the standard deviation of the natural logarithm of the above 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.

4.4.2.3 Step 3. Vertical Settlement

REDARS™ 2 also computes liquefaction-induced vertical settlements at each potentially liquefiable site. The Tokimatsu-Seed (T-S) (1987) model is used to perform this computation.

4.4.2.3.1 Input Data

The input data for this computation consists 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 those layers that are potentially liquefiable, the corrected standard penetration test blowcount must also be specified.

4.4.2.3.2 Vertical Settlement Computation

The T-S model consists of a series of curves of cyclic stress ratio vs. corrected standard penetration test blowcount, in which each curve corresponds to a different fixed value of volumetric strain (Fig. 4-9). 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 followed to estimate site-specific vertical displacements for a given scenario earthquake and simulation:

- For each saturated sandy layer at the site, compute the cyclic stress ratio. Enter the programmed T-S curves with this cyclic stress ratio and the layer's corrected standard penetration test blowcount 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

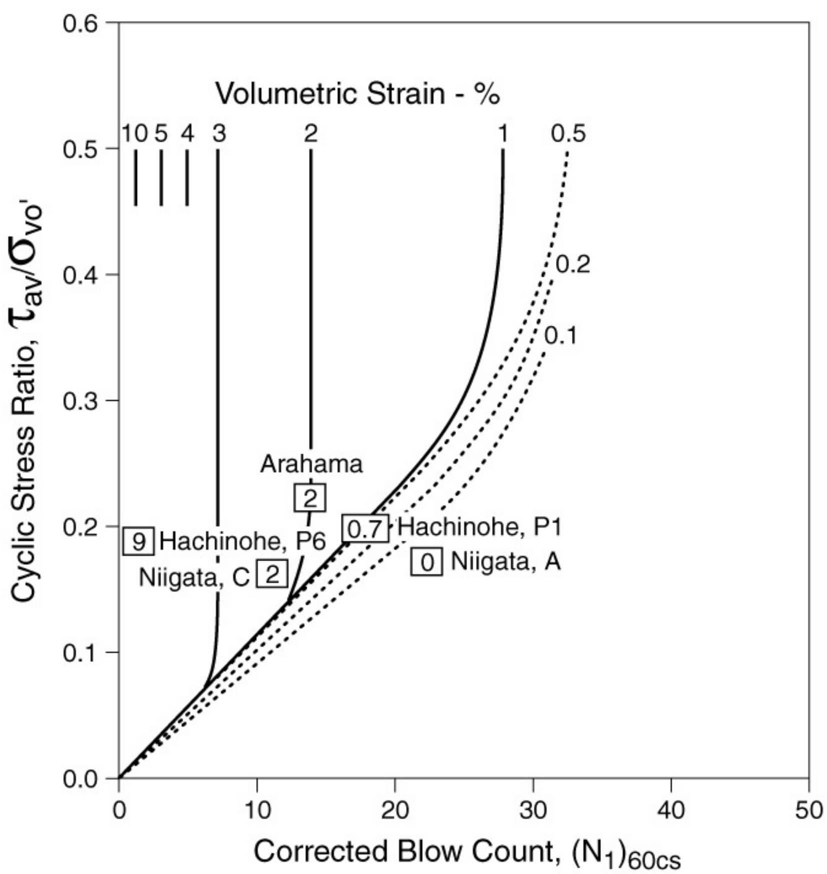


Figure 4-9. Liquefaction-Induced Volumetric Strains for Each Saturated Sand Layer in Site (Tokimatsu-Seed, 1987)

4.5 SUBTASK 2-4: SURFACE FAULT RUPTURE HAZARDS

4.5.1 Overview

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 to a spatially distributed highway system will be much more localized than will ground shaking hazards. Also, this surface rupture hazard 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.

Under Subtask 2.3, the RDT collaborated with members of Caltrans geotechnical engineering staff to review existing models for estimating surface fault rupture hazards for their applicability to Caltrans tectonic conditions and their consistency with the California earthquake models established under Subtask 2-1. As a result of this review, the Youngs et al. (2003) model was selected for inclusion into REDARS™ 2. The RDT's adaptation of this model is summarized below, and is described in more detail in Appendix F of Werner et al. (2006).

4.5.2 Hazard Evaluation Procedure

For highway systems that are located in regions where surface fault rupture is possible, this hazard should be evaluated by applying the following steps.

4.5.2.1 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 roadway system to be analyzed, in order to identify: (a) active faults in the region; and (b) any components within the roadway system that are crossed by or close to these faults.

4.5.2.2 Step 2. Permanent Ground Displacement Hazards

For each earthquake in the walkthrough table that is caused by rupture of one of these faults, 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. Then, those components identified in Step 1 as being on or near the fault along any part of its length are checked to see if they are on or near the segment of the fault that actually ruptured during this scenario earthquake. 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.

4.5.2.2.1 Input Data

All data needed to characterize the causative fault in order to estimate surface fault rupture hazards is provided in the earthquake data contained in the walkthrough table. As noted in Section 4.3.3, these data consist of: (a) the moment magnitude of the earthquake; (b) epicenter location; (c) depth to hypocenter and to seismogenic zone; (d) latitude, longitude, and depth of center of energy release; (e) fault type; (f) length, width, azimuth, and dip of each segment of fault rupture plane; (g) direction of rupture along fault plane; and (h) zone of deformation due to fault rupture (if specified by the user).

4.5.2.2.2 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.

4.5.2.2.3 Calculation of PGD (for Probabilistic SRA Application)

If any of the above conditions occur for any site in the highway-roadway 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.

4.5.2.2.4 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 5
TASK 3: UPDATED COMPONENT MODULE FOR CALIFORNIA APPLICATIONS

5.1 OBJECTIVE

Under Task 3, the RDT collaborated with Caltrans staff members in carrying out the following subtasks: (a) development of procedures for user-specified bridge fragility modeling; (b) use of Northridge Earthquake bridge damage observations to calibrate HAZUS99-SR2 fragility model for estimation of bridge damage due to ground shaking; (c) development of bridge damage repair models based on Caltrans experience during past earthquakes; (d) development of component vulnerability models for approach fills and pavements, based on Caltrans construction procedures and post-earthquake repair experience; and (e) development of component vulnerability model for Caldecott Tunnel.

5.2 USER-SPECIFIED BRIDGE FRAGILITY MODELING

5.2.1 <u>Background</u>

Implementation of REDARS™ 2 probabilistic SRA of highway-roadway systems requires the use of bridge fragility models. Figure 5-1 shows an example of such curves, which represent the probability that the bridge's traffic-carrying capacity will have different values at various times after the earthquake, as a function of the level of ground shaking at the bridge site. The models used to develop these curves include estimated effects of uncertainties in input material properties and in the seismic analysis procedure's ability to estimate the bridge's seismic response at various levels of ground shaking and for various possible damage modes.

REDARS™ 2 currently provides two fragility-modeling options for bridges in a highway-roadway system. The first type is for bridges with "typical" configurations whose disruption would not have a significant impact on the seismic performance of the overall highway-roadway system. For such bridges, which are most numerous in a typical system, simplified default models are used that are built into REDARS™ 2 and can be rapidly applied to large numbers of bridges during each of many simulations in a probabilistic SRA application. The REDARS™ 2 default models for bridges are described later in this chapter.

The second bridge modeling option involves the development of user-specified fragility curves for selected individual bridges within the highway-roadway system. As described later in this section, such curves are unique to an individual bridge and are based on the user's special seismic analysis of that bridge. These analyses are performed outside of REDARS™ 2, and the resulting fragility curves that are developed for the bridge are provided as input to REDARS™ 2, and are used instead of the default model to represent the bridge's seismic performance in the subsequent SRA. Figure 5-1 provides an example of user-specified fragility curves for a major river crossing near Memphis, Tennessee that were developed as part of a prior SRA of the Shelby County, Tennessee highway-roadway system by an early version of REDARS™ (Werner and Taylor, 2002). The development of such fragility curves for key California bridges is summarized in the remainder of this section.

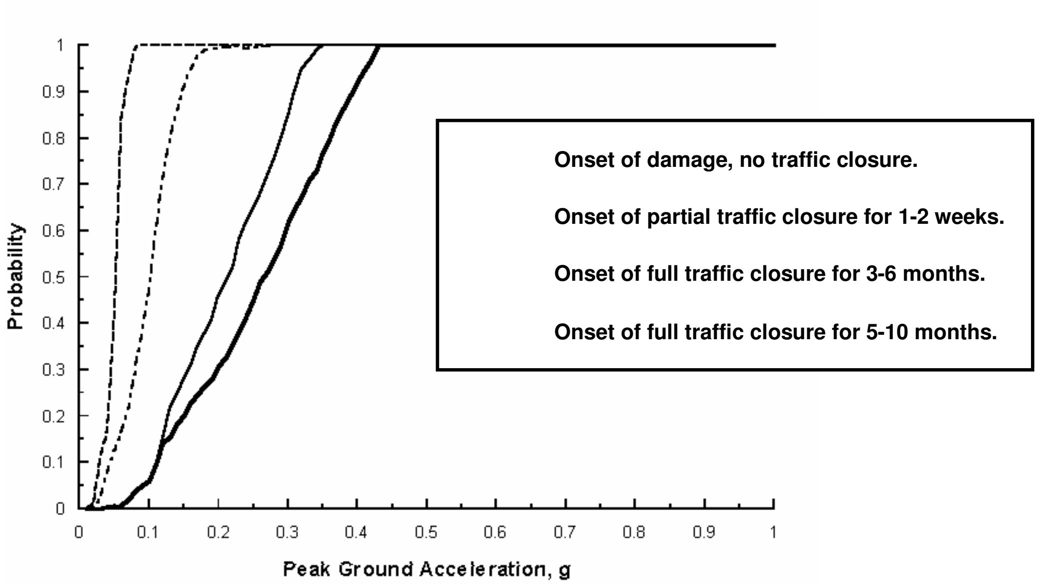


Figure 5-1. User-Specified Fragility Curves for Interstate-40 Crossing of Mississippi River at Memphis, Tennessee (Werner and Taylor, 2002)

Because the analyses leading to the development of user-specified fragility curves can be time-consuming, it is impractical to provide such curves for large numbers of bridges within the highway-roadway system. Therefore, the use of such curves should be restricted to those key bridges within the system: (a) that have long spans or other unusual configurations whose seismic performance cannot be well represented by the simplified default models; and/or (b) whose location within the system (e.g., along major non-redundant routes) is such that its extended loss of service due to earthquake damage would severely affect the roadway system's overall ability to accommodate post-earthquake traffic demands. For the remaining bridges that do not meet these criteria (and would normally constitute most of the bridges in the system), it is currently most practical to use the simplified default models that are built into REDARS™ 2.

5.2.2 Scope

The original purpose of this subtask was for the RDT to train Caltrans personnel in the development of user-specified fragility curves for major bridge structures, and to guide their development of such curves for two major bridges in the Northern California testbed highway-roadway system (see Fig 1-1 of Chapter 1). However, because of Caltrans' internal time and budget constraints, no personnel were available to participate in this fragility curve development activity. However, the training of Caltrans staff in the development of these curves did proceed to the extent that their staff was able to work collaboratively with the RDT to develop a general procedure for developing user-specified bridge fragility curves. This procedure, which can form the basis for the future development of such curves within Caltrans, is summarized in Section 5.2.3 below.

5.2.3 <u>Fragility Modeling Procedure</u>

This fragility modeling procedure involves of engineering analyses of the bridge, followed by the initial development, review, and finalization of the user-specified fragility curves.

5.2.3.1 Phase 1: Engineering Analysis

The engineering analysis phase of the fragility modeling procedure involves the various steps that are outlined below.

5.2.3.1.1 Step 1-1. Seismic Analysis

Step 1-1 involves analysis of the response of the bridge to various levels of ground shaking. However, in many cases, the development of new bridge models to carry out these analyses would not be needed. Instead, the engineer can utilize bridge models that have previously been developed as part of the bridge's seismic design or retrofit. The availability of such prior models would reduce the time needed to carry out this phase of the fragility model development. In this, it is noted that if the bridge is comprised of several segments, each with different structural configurations and/or materials of construction, different models for separate analysis of the seismic response of each bridge segment would be needed.

Next, the above models are used to analyze the seismic response of the bridge to various levels of ground motion. The range of different ground motion levels that is considered should be sufficient to lead to the onset of initial damage to the bridge, and also to the onset of collapse or to damage that would require replacement of the bridge. In addition, intermediate levels of ground motion that lead to various intermediate levels of bridge damage should be considered.

5.2.3.1.2 Step 1-2. Damage States

Under Step 1-2, the above seismic analysis results are interpreted in order to establish the bridge's damage state at each of the above levels of ground shaking. Each damage state would characterize the type, extent, and location of bridge damage at each level of ground shaking. This should not only represent the damage to each element of the bridge but, more importantly, should represent the damage to the overall bridge system (considering the redundancy of the various bridge elements and the possible consequences of each level of bridge system damage on the bridge's ability to accommodate traffic demands after the earthquake).

In addition, it is important for the damage states to be characterized in such a way as to facilitate the establishment of bridge repair requirements under Step 1-3. For example, such characterizations could include the extent of the remaining structural load-carrying capacity of the individual structural elements at various locations along the bridge, as well as the remaining capacity of the bridge system as a whole. Table 5-1 provides an example of element-level damage states used to develop user-specified fragility curves for the Interstate-40 crossing of the Mississippi River at Memphis, Tennessee (Werner et al., 2000; Werner and Taylor, 2002). Of course, the seismic performance of the overall bridge system will depend on the redundancies of these various elements at various locations along the length of the bridge.

Table 5-1. Element-Level Damage States for Interstate-40 Crossing of Mississippi River (Werner et al., 2000; Werner and Taylor, 2002)

Structural Element	Damage State					
	Slight to Minor		Repairable		Irreparable	
	C/D[1]	Description	C/D[1]	Description	C/D[1]	Description
Columns (Flexure)	1.0 - 0.50	No immediate closure or repair needed.	0.50-0.33	Moderate cracks, plastic hinging, or spalling. Column still structurally sound.	< 0.33	Column structurally unsafe due to severe damage. Replacement required.
Columns (Shear)	1.0 - 0.75	Minor cracking. Repair by epoxy injection of cracks. No immediate closure or repair needed.	0.75-0.50	Cracks widened, but column still has shear capacity. Can epoxy grout cracks.	< 0.50	Loss of concrete shear capacity. Replace column.
Bent Caps with Adequate Shear Reinforcement (Shear)	1.0 - 0.75	Minor cracking. Repair by epoxy injection of cracks. No immediate or repair needed.	0.75-0.50	Cracks widened, but bent cap still has shear capacity.	< 0.50	Loss of concrete shear capacity. Extensive repair or replacement of bent cap.
Bent Caps with Inadequate Shear Reinforcement (Shear)	1.0 - 0.75	Minor cracking. No closure or immediate repair needed.	--	--	< 0.75	Loss of shear capacity. Replace bent cap.
Bent Caps (Flexural)	1.0 - 0.50	No closure or immediate repair needed.	0.50-0.33	Moderate cracks, plastic hinging, or spalling. Bent cap still structurally sound.	< 0.33	Loss of flexural capacity. Extensive repair or replacement of bent cap.
Web Wall[2] (Shear)	1.0 - 0.50	No closure or immediate repair needed.	0.50-0.33	No closure or immediate repair needed.	< 0.33	No closure or immediate repair needed.
Footing (Rocking)	1.0 - 0.50	Minor rocking. No closure or immediate repair needed.	0.50-0.33	Moderate rocking. No closure or immediate repair needed.	< 0.33	Extensive rocking No closure or immediate repair needed.
Bearing	<1.0	Lift bridge. Install new dowels and bearings. No closure needed.	-	-	-	-
Seat Width (Deck Unseating and Dropping)	-	-	-	-	<1.0	Replace fallen deck span Repair expansion joint and bearing damage.

[1] These user-specified fragility curves were developed in the late 1990s. They are based on prior analyses of this bridge that were carried out in the early 1990s, and were based on an elastic capacity-demand procedure. This procedure is no longer used in current practice. Instead, if the analysis were to be carried out today, it would use more advanced analysis procedures that directly account for element nonlinearities and dynamic response. For this case, the onset of the above damage states would be based on limiting values of member displacement, strain, etc., rather than elastic capacity-demand ratio.

[2]Note that the function of a web wall is to provide lateral stability for wind. It is not a vertical load carrying member.

5.2.3.1.3 Step 1-3. Repair Requirements

Under Step 1-3, the procedure needed to repair the above bridge damage is established. This then provides the basis for estimating the bridge's repair costs and times, and its traffic-carrying capacity during repairs. This traffic-carrying capacity can be represented in terms of number of lanes available to carry traffic, allowable traffic speeds and weights on the bridge, etc. as the repairs proceed. That is, it would indicate those time periods during repairs when the bridge would be fully closed to traffic, partially open to traffic, and then fully open. This representation of repair requirements would, of course, be specific to the particular bridge being analyzed. It would also depend on whether emergency repair procedures (e.g., bonus incentive programs) are to be implemented.

Table 5-2 illustrates a process recently used to estimate repair costs, times, and functionality during repair of broken piles at a major seaport's marginal-wharf structure (Werner et al., 2002). A similar approach would be followed to estimate repair requirements for various levels and types of damage to a bridge structure.

Table 5-2. Example Estimate of Repair Requirements and Associated Costs and Times for a Broken 24-Inch Octagonal Pile (Not Beneath Crane Girder) at a Marginal-Wharf Structure of a Major Seaport (Werner et al., 2002)

Symptom	Crushed and badly damaged pile head. Rupture and displacement along inclined crack.		
Assessment	Broken pile. May also be broken or badly cracked below ground.		
Cause	In shallow water: excessive lateral displacement. In deeper water: P-delta column effect near expansion joints, torsion.		
Repair Method	Replace with new pile adjacent to broken pile.		
Repair Estimate	Work Item	Cost	Time
	Furnish 24" octagonal piles:		
	Set up in casting yard.	$5,000*	1 month*
	Cast 90-ft. x 24-in. diameter pile @ $34.00/pile.	$3,060	7 days
	Delivery to site.	$1,000	1 day
	Break hole in deck, cut rebar.	$4,000	2 days
	Remove riprap, replace.	$2,500	2 days
	Mobilize pile driver, first pile.	$10,000*	1 month*
	Drive pile.	$6,000	1 day
	Place and strip forms.	$3,200	3 days
	Splice rebar and add new rebar.	$2,800	2 days
	Concrete opening and cure.	$900	7 days
	Totals	$38,460	1 month + 25 days
			*Non-repeating and concurrent items

Note: For next broken pile, add $23,500 and 2 additional days. For large number of broken piles, assume that 4-6 piles can be driven per day, and reduce cost accordingly.

5.2.3.1.4 Step 1-4. Uncertainties

In Step 1-4, the engineer characterizes the uncertainties in the seismic analysis conducted in Step 1-1. This step would start with the engineer's qualitative assessment of his/her confidence in the results at each level of ground shaking considered in the analysis. These estimates may utilize sensitivity analyses, but would most likely be based on judgment and experience. The following issues may be relevant to this qualitative assessment of uncertainties:

- *Seismic Excitation Level.* What is the engineer's confidence in the analysis results as the levels of seismic excitation (and the degree of nonlinearity of the bridge response) increase?

- *Types of Damage.* What is the engineer's confidence in the ability of the analysis procedure to estimate the various types of damage that are predicted at the different levels of seismic excitation (i.e., whether the predominant damage modes involve significant shear vs. bending damage of columns, abutment wall cracking, shear key damage, expansion joint or other bearing damage, foundation damage (to footings, piles, etc.)?

- *Consequences of Damage.* What are the consequences of these levels and types of damage? That is, could the damage be of a brittle nature that leads to sudden loss of capacity of the bridge element, or would the damage be of a ductile nature for which the bridge would have sufficient reserve capacity to accommodate the seismic demands?

- *Input Parameter Uncertainties.* If the detailed seismic analysis is carried out using mean (or best-estimate) values of material properties and other input parameters, how might the predicted seismic response of the bridge be affected by reasonable variations of these parameters? That is, how would the responses of the bridge be distributed about the mean or best-estimate responses if variations of these input parameters are considered?

After completing these qualitative assessments, the engineer should represent the uncertainties quantitatively. This may be done by using coefficients of variation (*COV*), where a lower *COV* represents a greater confidence in the analysis results. Table 5-3 provides a guide for using *COV*s to characterize uncertainties, and Table 5-4 shows corresponding uncertainty estimates for one of the structure types along the length of the Interstate-40 crossing of the Mississippi River (Werner and Taylor, 2002).

Table 5-3. Guide for Use of *COV* to Represent Level of Uncertainty (Werner et al., 2002)

COV	Associated Level of Uncertainty in Results
0.2	High degree of confidence in results. Significant amount of supporting test data.
0.4 - 0.5	Reasonable confidence in results. Limited if any test data.
1.0	High uncertainty in results (for complex nonlinear systems). No supporting test data.
>1.0	Very high uncertainty for highly nonlinear and complex systems. No supporting test data.

Table 5-4. Example Uncertainty Estimate of Bridge Group B of Interstate-40 Crossing of Mississippi River (Werner and Taylor, 2002)

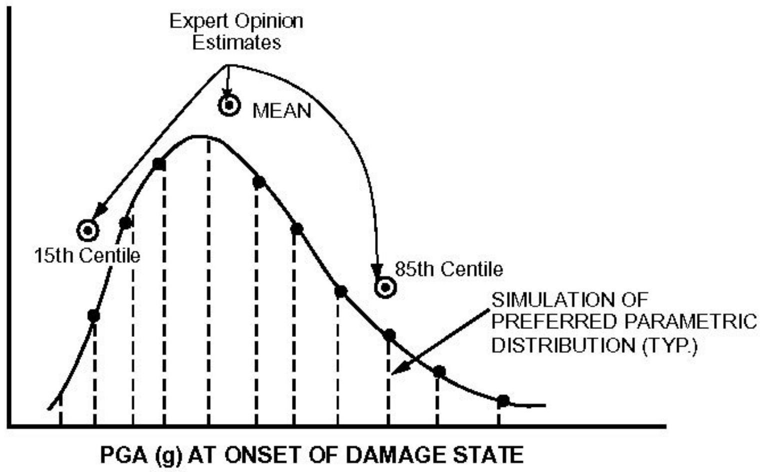
Bridge Group B has following attributes:

- Group B is 44-span bridge with length of 2,510 ft.
- Superstructure consists of prestressed concrete I-girders, except at Piers 55-58 (railroad track overcrossing), where superstructure consists of steel plate girders.
- Bridge supported on two-column concrete bents with concrete cap and pile foundation.
- Bronze expansion bearings and fixed elastomeric bearings

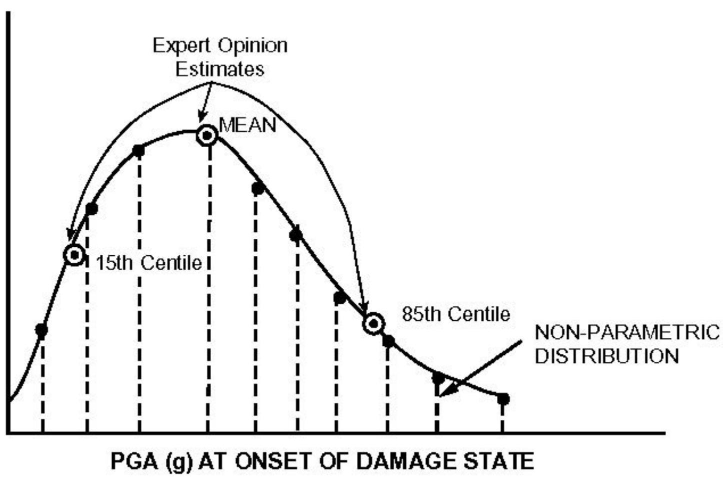
<table>
<tr><th colspan="3">Minor Damage</th><th colspan="3">Moderate Damage</th><th colspan="3">Severe Damage</th></tr>
<tr><td colspan="3">Damage State based on Analysis Results. Shear failure of bearing dowel bars at Piers 55-58. Minor shear cracking of bent caps at Piers 54-57. Moderate flexural cracking of short columns at Pier 56.
Traffic State: Closed for inspection for 3 days, and then partially open for 1-2 weeks during repairs.</td><td colspan="3">Damage State based on Analysis Results: Bearing dowel bars at Piers 54-58 sheared off. Bent caps at Piers 55 and 65 lose concrete component of shear strength. Moderate- to-extensive flexural damage to columns in Piers 54-57 and 65.
Traffic State: Closed for inspection and shoring for 3 days. Then, partially open to traffic for 2-4 weeks during repairs.</td><td colspan="3">Damage State based on Analysis Results: Bearing dowels at Piers 54-58 and 62-63 sheared off. Some shear damage to bent caps at nearly all piers, with extensive bent cap damage at Piers 49-55, 58, 59, and 65. Moderate flexural damage to columns at piers that cross railway.
Traffic State: Closed for 1-2 months during repairs (mainly at bent caps)</td></tr>
<tr><td colspan="3">Peak Ground Acceleration at Onset of Damage State, g</td><td colspan="3">Peak Ground Acceleration at Onset of Damage State, g</td><td colspan="3">Peak Ground Acceleration at Onset of Damage State, g</td></tr>
<tr><td>Mean</td><td>15th Centile</td><td>85th Centile</td><td>Mean</td><td>15th Centile</td><td>85th Centile</td><td>Mean</td><td>15th Centile</td><td>85th Centile</td></tr>
<tr><td>0.10</td><td>0.08</td><td>0.12</td><td>0.20</td><td>0.16</td><td>0.32</td><td>0.30</td><td>0.18</td><td>0.56</td></tr>
</table>

5.2.3.2 Phase 2: Initial Development of Fragility Curves

The initial development of the user-specified fragility curves under Phase 2 start with a series of parametric probability distributions that the user believes to be plausible candidates for fitting various targets of the type shown in Table 5-4. Then, each distribution is tested against the following "fitting" criteria, during which the distributions may be shifted or truncated by the user as illustrated in Figure 5-2: (a) the target mean and centile values specified by the engineer are reasonably well represented; (b) the resulting overall standard deviation fit's the engineer's assessment of the uncertainty in the threshold ground motion value for the onset of each damage state, relative to the other damage states; (c) the general shape and skewness of the resulting density function are plausible; and (d) each threshold ground motion value should satisfy transitivity (i.e., the probability of being in a lower damage state should exceed the probability of being in a higher damage state). The distribution that best meets these criteria is then used to construct the bridge's fragility curves.



a) Fit of Preferred Parametric Distribution to Expert Opinion Estimates
(Prior to Truncation and/or Shifting of Simulations)



b) Fit of Resulting Non-Parametric Distribution to Expert Opinion Estimates
(After Truncation and/or Shifting of Simulations)

Figure 5-2. Checking Fit of Various Probability Distributions to "Fitting" Criteria Listed on Page 5-7

5.2.3.3 Phase 3: Review and Finalization of Fragility Curves

Under Phase 3, the fragility curves developed under Phase 2 are independently reviewed by other bridge engineers not involved in the development of these curves. If warranted by comments provided during this independent review, the fragility curves may be revised. After completion of any necessary revisions, the user-specified fragility curves are finalized for input into REDARS™ 2.

5.3 CALIBRATION OF DEFAULT BRIDGE DAMAGE MODEL

5.3.1 Background

5.3.1.1 Statement of the Problem

The REDARS™ 2 Component Module contains a default model of the vulnerability of bridge structures subjected to earthquake ground motions. The bridge model described in HAZUS99-SR2 is currently being used for this purpose (FEMA, 2002). The implementation of this model in REDARS™ 2 is described in Werner et al. (2006).

During the initial phases of the development of REDARS™ 2, the various models that comprise the REDARS™ seismic risk analysis (SRA) methodology were independently checked (Cho et al., 2006b). Evaluation of the HAZUS99-SR2 bridge model was based on using this model to predict bridge damage states during the 1994 Northridge Earthquake, for 944 bridges within the most affected segments of the overall Los Angeles (LA) area highway system. Then, the predicted damage states for these various bridges were compared to their observed damage states, and these comparisons were used to gauge the acceptability of the HAZUS99-SR2 model for inclusion into REDARS™ 2 as a default bridge model.

These comparisons showed that the HAZUS99-SR2 model significantly overestimated the number of observed bridge collapses due to the Northridge Earthquake. This will cause REDARS™ 2 to substantially overestimate the effects of earthquake damage to the roadway system on post-earthquake traffic flows, since the program's default bridge repair model shows that by far the longest post-earthquake downtimes occur when the bridge is in a collapse damage state (see Section 5.4).

Therefore, it became clear that some adjustment of this model was needed before it could be included in REDARS™ 2 as a default model for estimating bridge damage due to ground shaking hazards. To meet this objective, refined statistical testing procedures were used to base this adjustment on a calibration against bridge damage observations from the Northridge Earthquake. This was accomplished by adjusting the model's structural capacity so that its predicted number of collapsed bridges and extensively-damaged bridges during the Northridge Earthquake was more consistent with observations. In this, differences in seismic performance of bridges with and without column jacketing were considered. This appendix describes this calibration effort.

It is noted that additional calibrations of this and other bridge models against damage observations from other major California earthquakes (e.g., the 1971 San Fernando and 1989 Loma Prieta Earthquakes) is clearly a worthwhile future study for further improving the current models. However, many of the bridges that are now in the areas affected by these earthquakes have attributes that differ substantially from the attributes of the bridges that were in place when these earthquakes occurred, and data that define these prior attributes are not readily available. For this reason, compilation of attribute data from bridges affected by these past earthquakes could not be attempted under this current project.

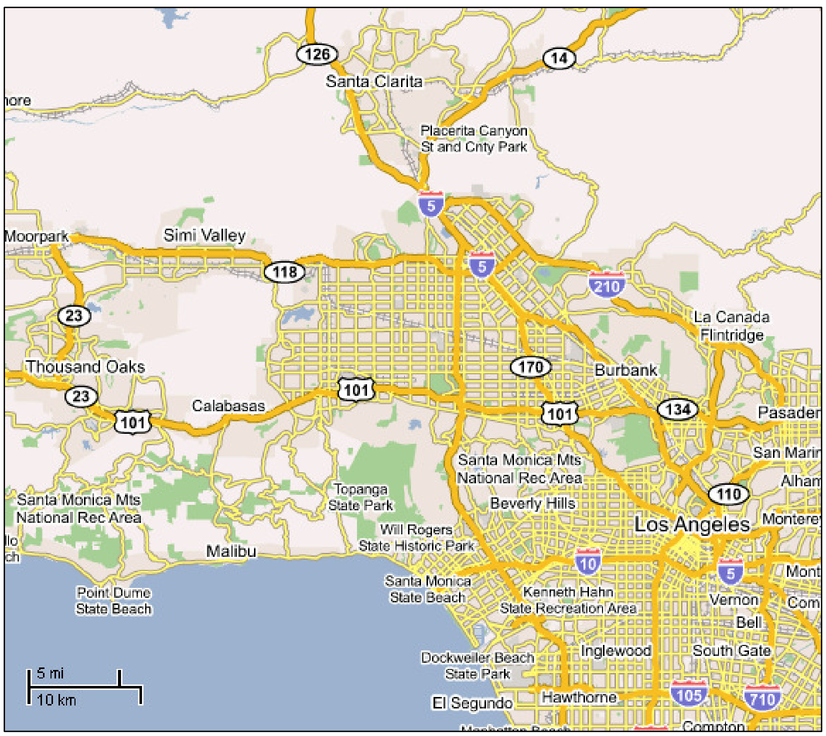
5.3.1.2 Section Organization

The remainder of this section is organized into three main subsections. Subsection 5.3.2 describes the system of bridges considered in this calibration task, and the Northridge-Earthquake's characteristics and bridge damage. The calibration procedure and results are provided in Section 5.3.3, and Section 5.3.4 contains concluding comments.

5.3.2 Bridge System and Earthquake Characteristics

5.3.2.1 System Extent

Figure 5-3 shows the highway-roadway system within the greater LA area whose bridges have been considered in this bridge-model calibration. This system extends from the town of Santa Clarita to the north to just beyond the Century Freeway (I-105) to the south, and from the Pacific coast east to just beyond downtown LA.



Source: maps.google.com

Figure 5-3. Extent of System of Bridges considered in this Calibration

The system contains the 944 bridges that were in place at the time of the Northridge Earthquake (see Figure 5-4). A total of 53 of these bridges had been column jacketed at the time of the earthquake. The structural attributes of these bridges that were input to the REDARS™ 2 analysis described below correspond to those of the in-place bridges at the time of the earthquake. This system is identical to the LA-testbed highway-roadway system used in the REDARS™ 2 demonstration application that is described in Appendix D.

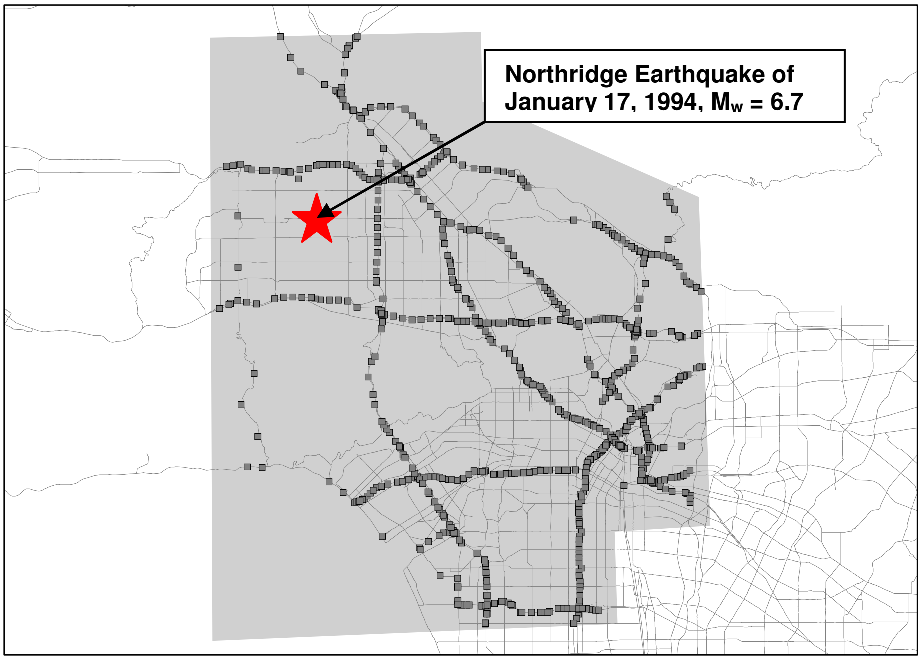


Figure 5-4. Earthquake and Bridge Locations (944 Bridges)

5.3.2.2 Northridge Earthquake and its Bridge Damage

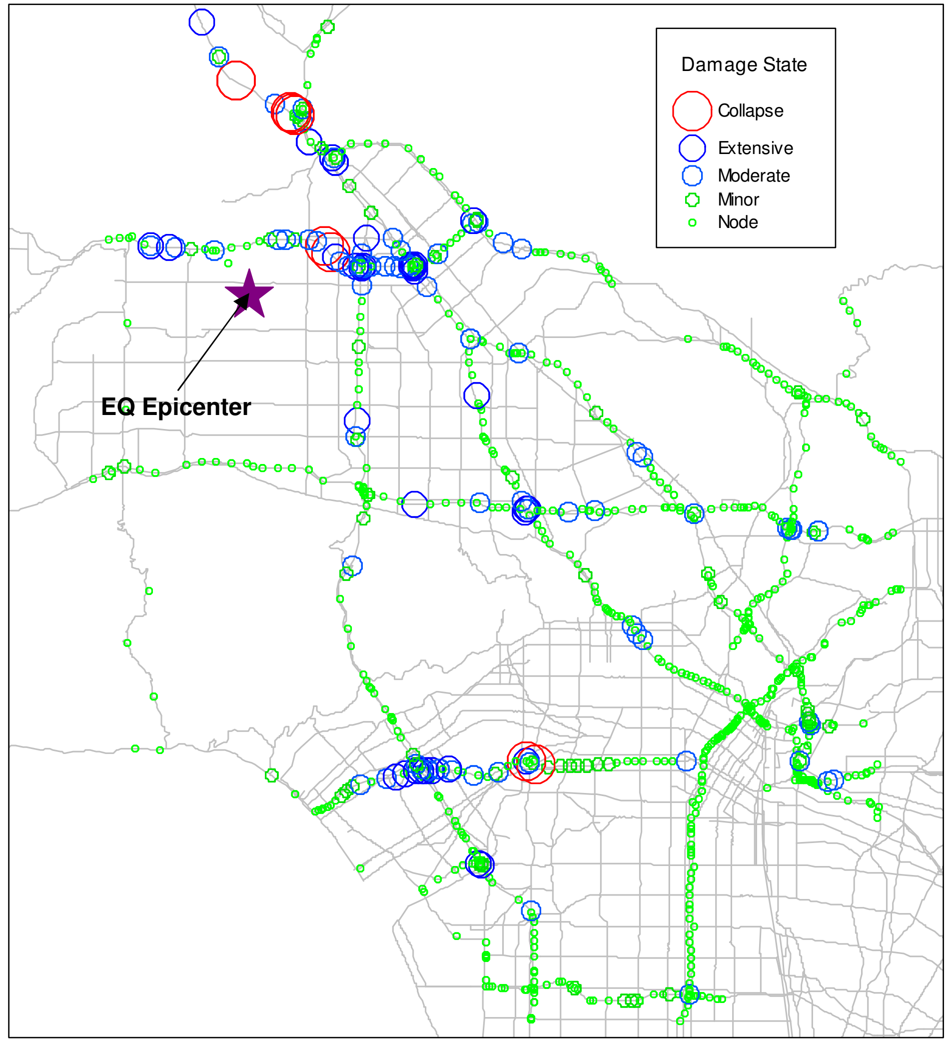
The Northridge Earthquake occurred on January 17, 1994. It had a moment magnitude of 6.7, and was centered in the northern part of the San Fernando Valley in the LA area (Fig. 5-4). Table 5-5 and Figure 5-5 provide a breakdown of the bridge damage due to the Northridge Earthquake. They show that 10 of the bridges collapsed during the earthquake and 36 were extensively damaged. None of the column-jacketed bridges collapsed during the earthquake.

Table 5-5. Breakdown of Bridges by Damage State and Level of Retrofit

Damage State		Bridges with No Column Jacketing	Bridges with Column Jacketing	Total
Designation	Description			
5 (Collapse)	Collapse of any column, or unseating of deck span leading to collapse of deck. Tilting of substructure due to foundation failure.	10	0	10
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	34	2	36
3 (Moderate)	Any column experiencing moderate shear cracking and spalling (with columns still structurally sound), moderate movement of abutment (< 5.1 cm), extensive cracking and spalling of shear keys, damaged shear key connections, bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of approach.	69	9	78
2 (Minor)	Minor cracking and spalling of the abutment, cracks in abutment shear keys, minor spalling and cracking at hinges, minor spalling of column requiring no more than cosmetic repair, or minor cracking of deck.	64	6	70
1 (None)	First yield	714	36	750
		891	53	944

Route	Bridge		
	Name	State Bridge Number	
		Before 1994	After 1994
Interstate-5	Gavin Canyon Undercrossing (2 bridges)	53-1797 R/L	53-2790 R/L
Interstate-5 and State-Route-14 Interchange	North Connector Overcrossing	53-1964F	53-2796F
	South Connector Overcrossing	53-1960F	53-2795F
	North Separator Overcrossing	53-1963F	53-2797F
	South Separator Overcrossing	53-1960G	53-2795G
State Route 118	Mission-Gothic Undercrossing	53-2205	53-2793
	Bull Creek Canyon Channel Undercrossing	53-2206	53-2794
Interstate 10	Fairfax-Washington Undercrossing	53-1580	53-2792
	La Cienega-Venice Undercrossing	53-1609	53-2791

a) Collapsed Bridges (Basoz and Kiremidjian, 1998)



b) Locations of Damaged Bridges

Figure 5-5. Bridge Damage due to 1994 Northridge Earthquake

5.3.3 Calibration Procedure and Results

5.3.3.1 Overview

The calibration of the HAZUS99-SR2 model to Northridge Earthquake bridge-damage observations involved the use of REDARS™ 2 to carry out a series of conditional probabilistic analysis of the highway system shown in Figure K-1. In this analysis, the earthquake event was fixed (as the Northridge Earthquake), and uncertainties in the estimation of site-specific ground motions and bridge damage states were considered. In these conditional probabilistic analyses, the bridge damage-capacity term in the HAZUS99-SR2 model was systematically incremented, and the joint probability of achieving 10 collapses and 36 extensively-damaged bridges in the system was computed. The incremented values of the structural capacities that led to the largest joint probability of occurrence of 10 collapses and 36 extensively damaged bridges was selected to represent the calibrated capacities in the HAZUS99-SR2 bridge model. In addition, the locations of the bridges with the largest joint probabilities of occurrence of these major levels of damage were compared to the actual locations of this bridge damage (see Fig. 5-5b) to be sure that they compared reasonably well. This process is further described in the following subsections.

5.3.3.2 Starting Points

5.3.3.2.1 HAZUS99-SR2 Structural Capacity Representation

The HAZUS99-SR2 model represents structural capacities for unretrofitted bridges as the value of the spectral acceleration at a period of 1.0 sec. ($S_a(1.0)$) that leads to the onset of each of the five damage states listed in Table 5-5. This spectral acceleration capacity for each damage state is expressed by the following equation that is consistent with the lognormal probability distribution assumed by the HAZUS99-SR2 bridge model.

$$\ln C_{i,j}'' = \ln(\alpha_i C_i') + \beta_i X_j \qquad (5\text{-}1)$$

In Equation 5-1, C_i'' is the spectral-acceleration capacity leading to the onset of the i^{th} damage state for the j^{th} simulation including effects of uncertainties, C_i' is the median value of this spectral-acceleration, X_j is a uniform random variate for the j^{th} simulation, and α_i and β_i are the mean value and standard deviation respectively of the uncertain structural capacity for the i^{th} damage state.

The goal of this calibration was to obtain modified values of α_i and β_i for Damage States 5 (collapse) and 4 (extensive damage) that result in the largest joint probability of occurrence of 10 collapsed bridges and 36 extensively-damaged bridges (as per the Northridge Earthquake bridge-damage observations). In this, estimation of the number of bridge collapses is particularly important, since the REDARS™ 2 default repair model that is described in Section 5.4 indicates that by far the most extensive downtimes will occur if a bridge has collapsed; i.e., the downtimes associated with the lesser damage states will be much shorter.

5.3.3.2.2 Analysis Parameters and Uncertainties

5.3.3.2.2.1 Ground Motion Uncertainties

As noted earlier, uncertainties in ground-motion estimates as well as damage-state estimates are considered in this calibration procedure. This is because median values of ground motions -- represented here as peak values of spectral acceleration at periods of 1.0 sec. and 0.3 sec.-- which are denoted as $S_a(1.0\sec)$ and $S_a(0.3\sec)$ respectively) -- may not represent the actual levels of ground shaking that affected the seismic performance of the various bridges during the Northridge Earthquake. Since these actual levels of ground shaking will never be known (without strong-motion accelerometers to actually record the motions), it is essential to consider uncertainties in their estimates so as to represent the broad scatter of possible ground shaking levels at a particular bridge site. This scatter can be important for explaining why some bridges have performed well during an earthquake, whereas others have not.

5.3.3.2.2.2 Ground Motion Models

In addition, experience has shown that different ground motion models will not always provide similar estimates of site-specific ground motions, particularly for earthquake magnitude and distance combinations for which little or no strong-motion recordings are available. Therefore, under this task, special care has been taken to use established ground-motion models that were developed by well-respected geoscientists. Two ground motion models that meet these criteria have been used here -- the Abrahamson-Silva (1997) and the Sadigh et al. (1997) models. In this, the Abrahamson-Silva model was used in most of the calibration analyses, but results were also developed using the Sadigh et al. model so that the sensitivity of the calibration results to these different models could be assessed. For each of these models, "intra-event" uncertainty factors were established in collaboration with Chiou (2005) and are shown in Table 5-6.

Table 5-6. Assumed Lognormal Standard Deviations for Representing Intra-Event Uncertainties (Chiou, 2005)

Ground-Motion Model	Lognormal Standard Deviation for Representing Intra-Event Uncertainties	
	$S_a(1.0\sec.)$	$S_a(0.3\sec.)$
Abrahamson-Silva (1997)	0.56	0.50
Sadigh et al. (1997)	0.54	0.50

5.3.3.2.2.3 Shape of Fault-Rupture Plane

Yet another parameter of interest is the assumed shape of the fault-rupture plane for the Northridge Earthquake. Both rectangular and non-rectangular shapes have been considered in this analysis. Owing to the complexity of modeling multiple scenario earthquakes as having non-rectangular fault-rupture planes, REDARS™ 2 currently uses rectangular rupture planes. However, in this calibration analysis, some calculations were also carried out using non-rectangular rupture planes, to facilitate assessment of the sensitivity of the calibration results to this parameter.

5.3.3.2.2.4 Calibration Philosophy

If large ranges of α_i and β_i values are considered in this calibration process, the number of possible combinations of α_i and β_i to be considered could become so large as to be impractical. To avoid this possible situation, it was decided to constrain the number of solutions to be considered by assuming that β_i for the modified model will have a fixed value of 0.35, which is approximately the so-called "aleatory" component of the uncertainties in the original development of the HAZUS99-SR2 bridge model (see Dutta and Mander, 1998). Note that the current HAZUS99-SR2 bridge model as documented in NIBS (2002) is based on $\beta_i = 0.6$, which also includes the epistemic component of the uncertainties. However, we found that this current model (with $\beta_i = 0.6$) already significantly overestimated the number of bridge collapses during the Northridge Earthquake. To modify this result and provide more favorable comparisons with the observed number of bridge collapses, one would not increase this uncertainty factor β_i; i.e., this uncertainty factor would only be increased if the HAZUS99-SR2 model significantly underestimated the bridge collapses.

Therefore, all calibrations of this model involved adjustments of α_i only. This means that the modified values of α_i and β_i that were developed from this calibration would not represent optimum comparisons with Northridge Earthquake bridge-damage observations. Rather, it was intended that the calibrations should lead to a range of plausible and statistically acceptable values, particularly since the number of bridge collapses from the Northridge Earthquake represents experience from only one earthquake.

Finally, as noted below, calibrations of α_i against Northridge Earthquake bridge damage observations were based on a series of conditional probabilistic analyses that considered a fixed earthquake event corresponding to the Northridge Earthquake and uncertainties in the ground motion and structural capacity estimates. In this, α_i values for Damage States 5 and 4 were incremented, and the joint probability of occurrence of 10 bridge collapses and 36 extensively damaged bridges was estimated for each incremented value. Those values of α_i for these damage states that led to the highest joint probability of occurrence of the above number of collapsed and extensively damaged bridges were selected for incorporation into this modified model. Each of these conditional probabilistic analyses included 4,000 simulations, which should be sufficient to capture most of the extremely low probabilities that the model accounts for the number of collapses and extensively damaged bridges. For situations in which even 4,000 simulations were insufficient to capture some of the extremely low probabilities, a normal distribution was simulated as a proxy to estimate these low probabilities.

5.3.3.3 Analysis Steps and Results

5.3.3.3.1 Step 1: Develop REDARS™ 2 Model of Highway-Roadway System

In Step 1, a REDARS™ 2 model of the highway-roadway system shown in Figure 5-3 was developed. This model is identical to that used in the demonstration analysis of the LA roadway system that is described in Appendix D; however, now, the model is used here only to estimate bridge damage states. The following model characteristics are relevant to this application:

- The model includes all of the system's freeways and major arterials. It contains 1,694 nodes and 5,100 links, whose locations and traffic capacities were obtained from the Highway Performance Monitoring System (HPMS) and the National Highway Planning Network (NHPN), as accessed by the REDARS™ 2 Import Wizard (Cho et al., 2006a).
- Structural attributes of the 944 bridges in this system were obtained from the National Bridge Inventory (NBI) database, as also accessed through the REDARS™ 2 Import Wizard. Data from Caltrans' statewide bridge database were used to update some of these attributes, and to also identify the 53 bridges in the system that had been column-jacketed when the Northridge Earthquake occurred. The improved seismic performance of the column-jacketed bridges was represented by using retrofit enhancement factors for Damage States 5 and 4 that were developed by Shinozuka (2004) and are described in Appendix G of Werner et al. (2006).
- The soil conditions within the system are identical to those described in Appendix D, and are shown in Figure 5-6.

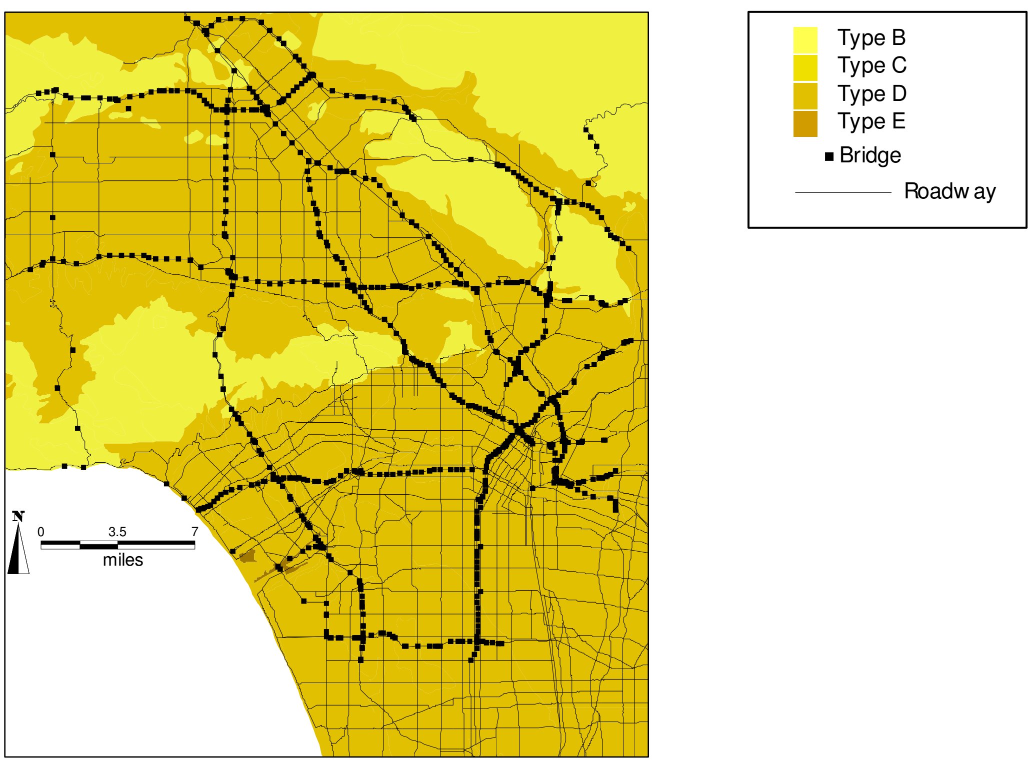


Figure 5-6. Soil Conditions at Bridge Sites

5.3.3.3.2 Step 2: Estimate Probability of Collapse using α_i and β_i Factors used in Current HAZUS99-SR2 Model

The HAZUS99-SR2 model currently uses αi and β_i factors of 1.0 and 0.35 respectively for all damage states. Under Step 2, these factors were used in a REDARS™ 2 conditional probabilistic analysis in order to estimate the probability of occurrence of 10 bridge collapses. If this probability turns out to be very small, as anticipated, development of modified values of α_i for damage states 5 and 4 under the previously-described strategy is further justified.

This analysis involved 4,000 simulations in which, for a fixed earthquake event corresponding to the Northridge Earthquake, uncertainties in ground motion and damage state estimates are included. Its results, which are displayed in Figure 5-7, show that this computed probability of occurrence of 10 collapses is indeed very small. It also yields a median estimate of 39 bridge collapses, which is 3.9 times larger than the observed number of collapses. This indicates that current HAZUS99-SR2 bridge model in its current form substantially overestimates the observed number of bridge collapses during the Northridge Earthquake.

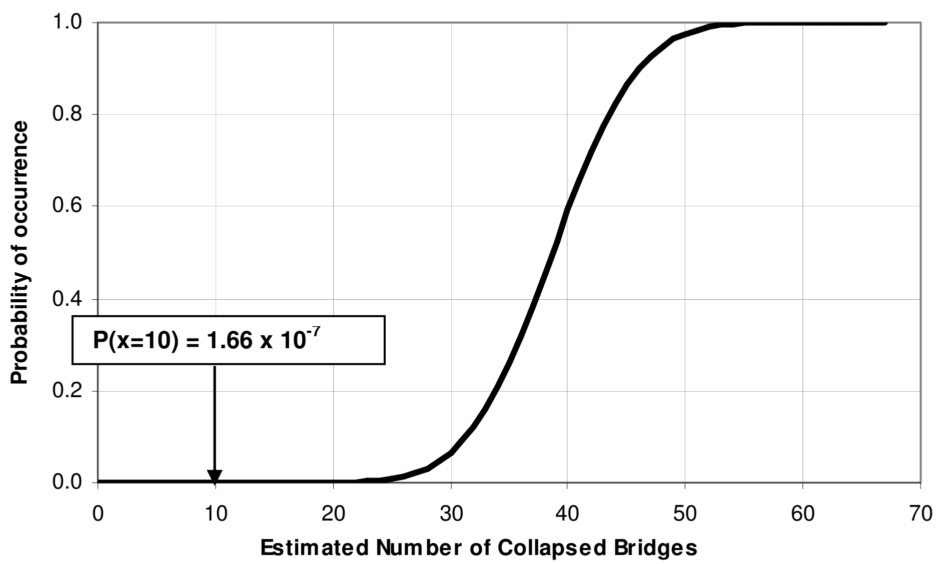


Figure 5-7. Number of Bridge Collapses Estimated to have Collapsed using Current HAZUS99-SR2 Bridge Model (α_5 = 1.0 and β_5 = 0.35) using Abrahamson-Silva (1997) Ground-Motion Model and Rectangular Fault-Rupture Model

5.3.3.3.3 Step 3: Develop Modified Model that Maximizes Probability of 10 Collapses

Under this step, a modification to the HAZUS99-SR2 model's current values of α_5 and β_5 was developed that maximizes the probability of 10 bridge collapses. This modification was based on the following procedures:

- As previously noted, the parameter β_5, which is the standard deviation of lognormal distribution represented by Equation 5-1, was assumed to have a fixed value of 0.35 (which is the same as the value of β_5 used in the current HAZUS99-SR2 model.
- For this fixed value of β_5 = 0.35, the parameter α_5 was incremented between values of 0.8 and 2.2 and, for each α_5 value, the probability of occurrence of 10 collapses was computed. In this, 141 different values of α_5 were considered (in which α_5 was incremented by 0.01 within the above limits) and, for each discrete value of α_5, 4,000 simulations (i.e., repeated applications of the Northridge Earthquake) were developed according to Equation 5-2, in which x_5 is the number of collapsed bridges.

$$P(x_5 = 10|\alpha_5) = P(x_5 \leq 10|\alpha_5) - P(x_5 \leq 9|\alpha_5) \tag{5-2}$$

- From this, the value of α_5 that led to the largest value of the probability of 10 collapses was identified, and normalized to 1. Figure 5-8 shows that when α_5 = 1.43, the largest probability of occurrence of 10 collapses was obtained.
- The final operation under this step involved identifying all values of α_5 that are within 80-percent of the above value. This range of α_5 values was used in the joint probability calculations carried out under Step 4.

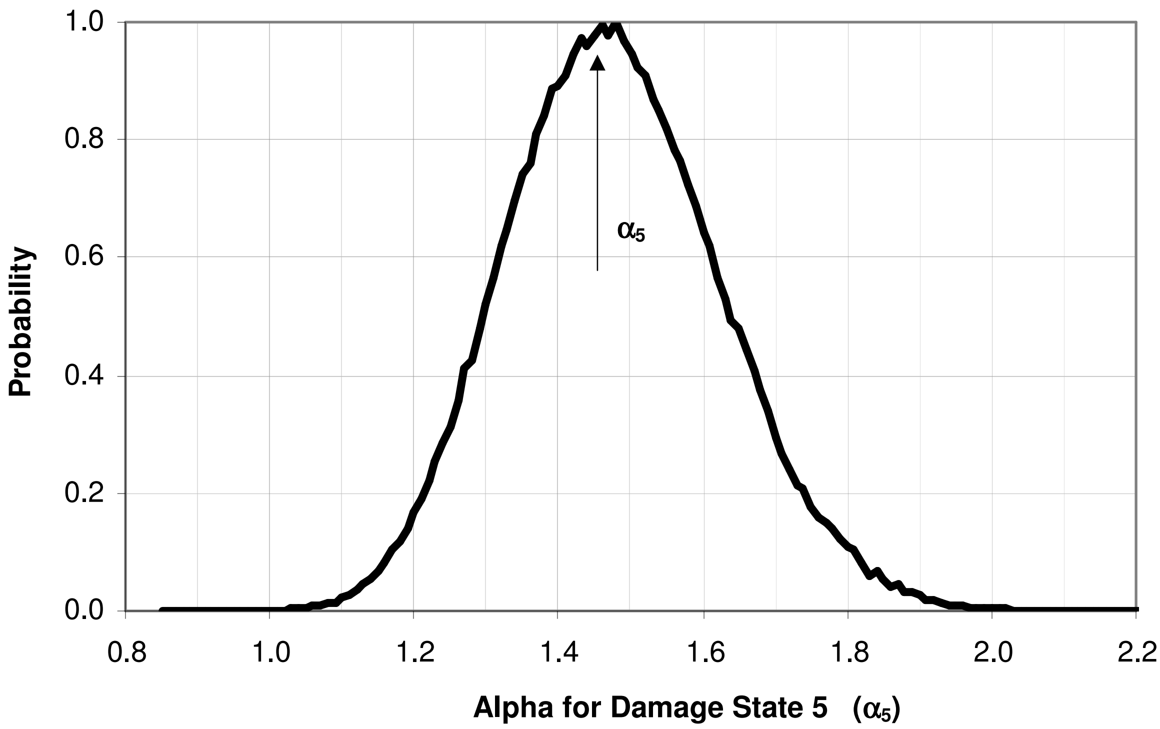


Figure 5-8. Normalized Probability of Occurrence of 10 Collapses, as a Function of α_5 (for β_5 = 0.35) using Abrahamson-Silva (1997) Ground-Motion Model and Rectangular Fault-Rupture Model

5.3.3.3.4 Step 4. Develop Modified Model that Results in the Maximum Joint Probability of Occurrence of 10 Collapsed Bridges and 35 Extensively-Damaged Bridges

Under this step, combinations of parameters α_5 and α_4 were identified that, together with $\beta_5 = \beta_4 = 0.35$, resulted in the highest joint probability of occurrence of 10 collapsed bridges and 36 extensively-damaged bridges according to Equation (5-3). As noted above, values of α_5 were used here that were within ± 80-percent of the value that led to the largest probability of 10 bridge collapses in Step 3.

$$P(x_5 = 10, x_4 = 34 | \alpha_5, \alpha_4) = P(x_5 = 10 | \alpha_5) \cdot \{P(x_4 \leq 34 | \alpha_5, \alpha_4) - P(x_4 \leq 33 | \alpha_5, \alpha_4)\} \quad (5\text{-}3)$$

where x_5 is the number of collapsed bridges and x_4 is the number of extensively damage bridges.

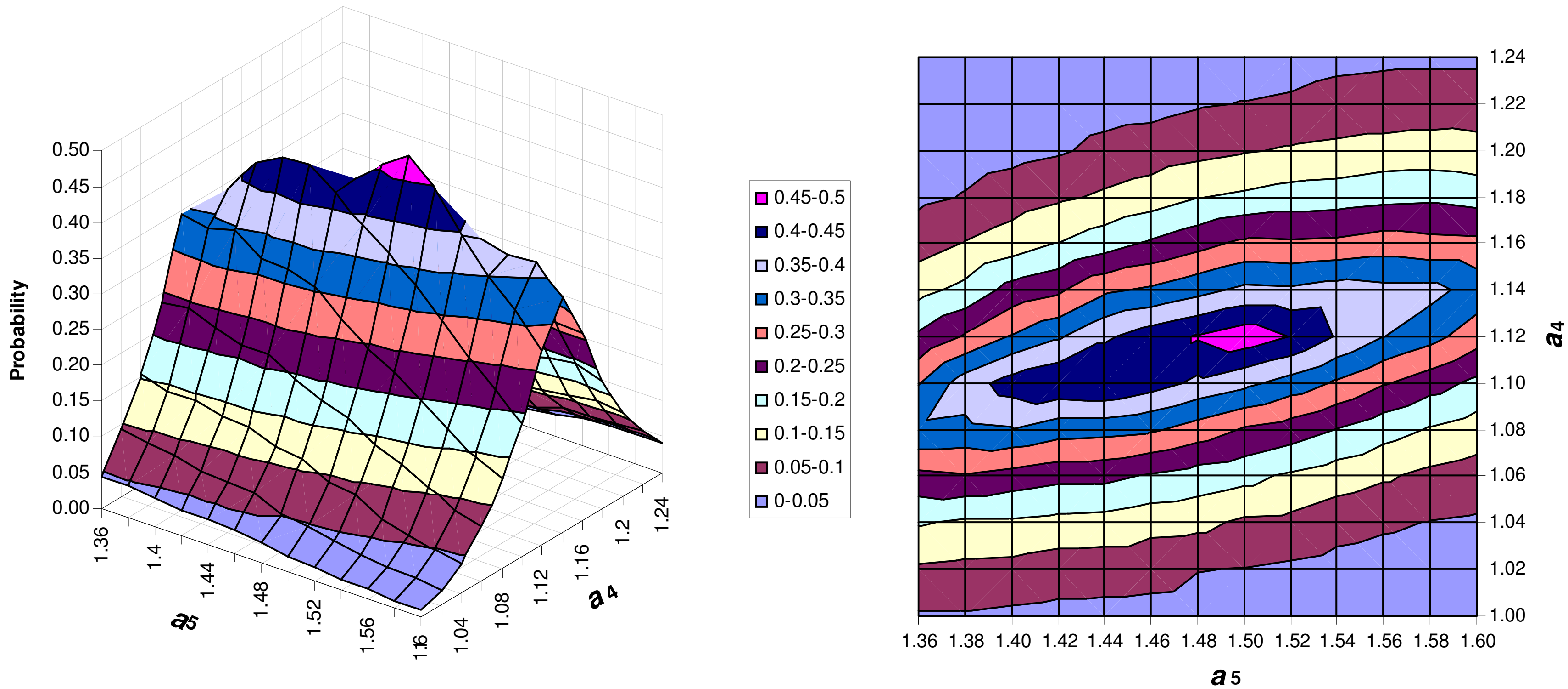
The results of this step are provided in the joint density function that is shown in Figure 5-9. From this, the α_I and β_i values for Damage States 5 and 4 that represent the modifications of the HAZUS99-SR2 model that were developed from this calibration (using the Abrahamson-Silva (1997) ground-motion model and a rectangular fault-rupture model) are shown in Table 5-7.

Table 5-7. Summary of Modifications to HAZUS99-SR2 Model (based on use of Abraham-Silva (1997) Ground Motion Model and Rectangular Fault-Rupture Model

Damage State	α_i	β_i
5 (Collapse)	1.50	0.35
4 (Extensive)	1.12	0.35
3 (Moderate)	1.0	0.35
2 (Minor)	1.0	0.35

5.3.3.3.5 Step 5: Perform Sensitivity Evaluations

Each of the previous steps was carried out using the Abrahamson-Silva (1997) ground-motion model and a rectangular model of the fault-rupture plane. Under Step 5, the calculations carried out under these steps were repeated, using the Sadigh et al. (1997) ground motion model and a non-rectangular representation of the fault-rupture plane (Fig. 5-10). The purpose of these calculations was to evaluate the sensitivity of the results to variations in ground motion models (where both the Abrahamson-Silva and Sadigh et al. models are well accepted) and to differences in how the fault source is modeled. Results of these analyses (Table 5-8) show that the values of α_5 and α_4 values increase by at most 15-percent and typically less than 10-percent due to these changes in the ground motion model and the modeling of the fault source.



a) Three-Dimensional View **b) Plan View**

Figure 5-9. Combined Density Function showing Combinations of α_5 and α_4 Values that Result in Largest Probability of Occurrence of 10Collapsed Bridges and 34 Extensively-Damaged Bridges using Abrahamson-Silva (1997) Ground-Motion Model and Rectangular Fault-Rupture Model

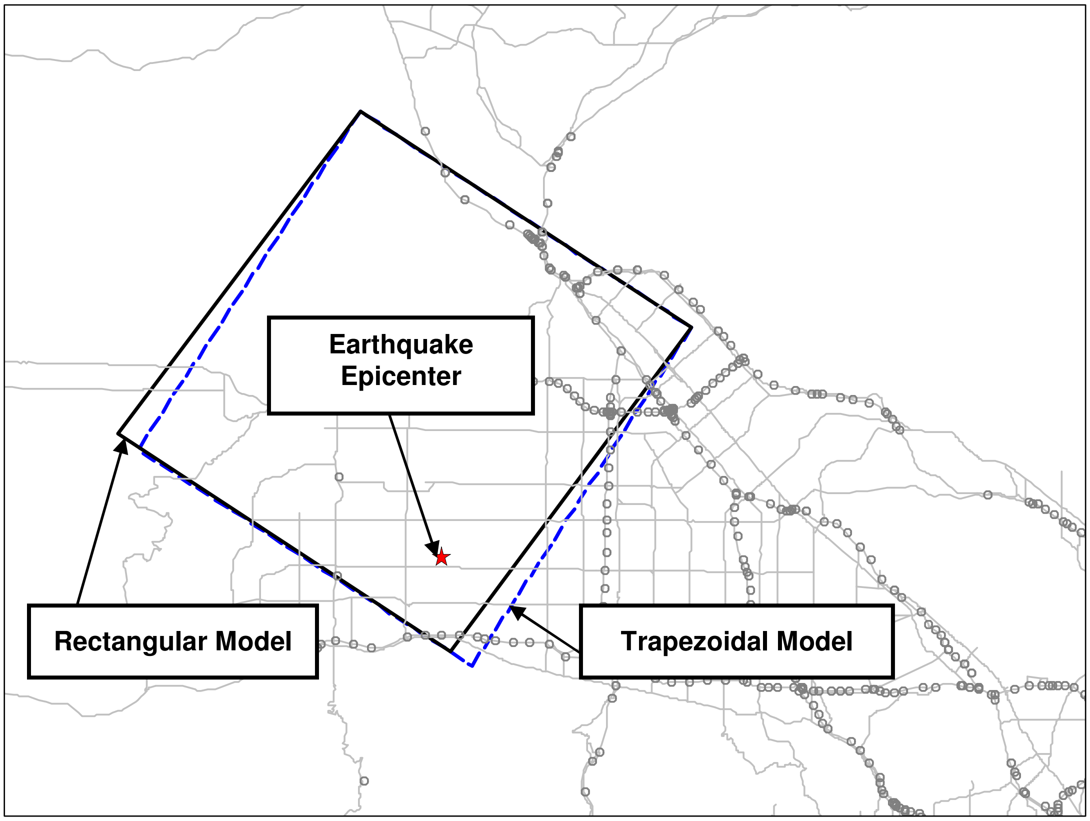


Figure 5-10. Rectangular and Trapezoidal Models of Fault-Rupture Plane for Northridge Earthquake (Chiou, 2005)

Table 5-8. Sensitivity of Calibrated Bridge Model Parameters to Changes in Ground Motion Models and Models of Fault Rupture Plane (Chiou, 2005)

Damage State	Values of α_i (for fixed β_i = 0.35)			
	Abrahamson-Silva (1997) Ground-Motion Model		Sadigh et al. (1997) Ground-Motion Model	
	Rectangular Model of Fault-Rupture Plane	Trapezoidal Model of Fault-Rupture Plane	Rectangular Model of Fault-Rupture Plane	Trapezoidal Model of Fault-Rupture Plane
5 (Collapse)	1.50	1.65	1.61	1.72
4 (Extensive)	1.12	1.20	1.14	1.22
3 (Moderate)	1.00	1.00	1.00	1.00
2 (Minor)	1.00	1.00	1.00	1.00

5.3.4 Concluding Comments

This section has shown how refined statistical analysis procedures can be used to calibrate a bridge model's damage predictions against observed bridge damage from an actual earthquake. This analysis was motivated by early assessments of the HAZUS99-SR2 bridge model that showed the model to substantially overestimate the observed number of bridge collapsed due to the Northridge Earthquake. Because this HAZUS model is currently the REDARS™ 2 default model for estimating damage to bridges from ground shaking, it was clear that the above overestimates could have significant effects of the losses due to earthquake damage to a highway-roadway system that would be estimated by REDARS™ 2. Therefore some adjustment to the model was needed.

The results from this appendix show that adjustments to the HAZUS99-SR2 bridge model to reduce these overestimates of bridge collapses were successfully carried out. However, it is important to recognize that these model calibrations and adjustments have been based on damage observations from only one earthquake. Clearly, if such calibrations were to be made against bridge damage observations from other earthquakes or for other highway systems in different regions of the United States, the adjustments to the HAZUS99-SR2 model would most probably differ from those developed here from calibrations against Northridge Earthquake bridge damage observations[3].

However, the ability of the engineering profession to carry out other calibrations with observed bridge damage from other earthquakes located in other parts of the country, where bridge construction practices will differ from those in California. This is because of the lower seismic activity in most of these other regions relative to California and also because many transportation departments have not maintained electronic databases of structural attributes of those bridges that were in place at the time of prior earthquakes, particularly if the earthquake occurred many years ago. Nevertheless, this situation will undoubtedly improve in the future, as computerized databases of bridge attributes become more common. Where such calibrations are possible, they are highly recommended as a way to use actual earthquake data to its fullest advantage in order to improve the safety of highway-roadway systems located in an earthquake-prone region.

5.4 DEFAULT REPAIR MODELS FOR BRIDGES

5.4.1 Background

This section summarizes the default model used by REDARS™ 2 to estimate repair of damage to bridges subjected to ground shaking and PGD hazards. For each of these damage states, this default repair model provides first-order estimates of corresponding bridge repair costs,

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[3] During this project, Caltrans' project staff investigated the possibility of also calibrating the HAZUS99-SR2 model against observed bridge performance during the 1989 Loma Prieta Earthquake. However, because the highway system in the Bay Area has changed substantially since the earthquake, and data to characterize the system at the time of the 1989 earthquake were not readily available, this additional calibration was not attempted.

durations, and traffic states as the repairs are proceeding. As noted earlier in this report, these first-order repair models can be overridden by the user, either: (a) for individual bridges within the roadway system being analyzed, (e.g., for major bridges along non-redundant roadways where more refined damage and repair estimates are appropriate); or (b) for all bridges throughout the roadway system (e.g., to account for bridge construction and repair practices and resources in the region being analyzed that differ from those represented by these models). This repair model is also described in Appendix G of Werner et al. (2006).

5.4.2 Assumptions

The REDARS™ 2 default bridge repair model is based on the various assumptions that are summarized below.

5.4.2.1 California-Based Model

This default repair model was developed in collaboration with senior bridge engineering and maintenance personnel at the California Department of Transportation (Caltrans) in Sacramento CA, and is based on their judgment and experience.. Therefore, the model is applicable to California bridges and to the construction types, maintenance practices, and post-earthquake repair resources and strategies that Caltrans has developed. REDARS™ 2 users from outside of California should modify this default model as appropriate to best represent the construction, maintenance, and repair procedures/resources for their particular roadway transportation system.

A benefit of this default repair model is that it incorporates Caltrans' extensive experience in post-earthquake bridge damage assessment and repair that is unmatched elsewhere in the United States. Also, this default repair model can be readily modified by REDARS™ 2 users, to enable them to incorporate future adjustments to the model or to evaluate the sensitivity of the estimated losses to possibly changes in repair strategy (such as including a bonus-retrofit program for repair of bridges along major freeways).

5.4.2.2 Qualitative Damage State Descriptions

This default model is based on the HAZUS99-SR2 damage state descriptors listed in FEMA (2002). However, these qualitative damage descriptors do not provide information on the types, extents, and locations of earthquake damage throughout the bridge system with a level of detail that would ordinarily be needed to estimate bridge system repair requirements. There is a well-recognized need for research to develop next-generation bridge damage models that include improved bridge-system damage descriptions for estimation of repair procedures, costs, times, and traffic states. (TCW, 2003 and 2005).

As noted earlier, the HAZUS99-SR2 model assumes that PGD can only cause incipient unseating and collapse of a bridge (corresponding to Damage States 4 and 5). Therefore, in this repair model, it is assumed that if Damage States 4 or 5 do occur, the repair strategies, costs, time, and effects on bridge traffic states during the repairs will be the same regardless of whether this damage was caused primarily by ground motions or PGD. It is also assumed that the occurrence of Damage States 2 or 3 due to PGD hazards at bridges is excluded from this model. Nevertheless to enable users to consider the possible occurrence of Damage States 2 and 3 due to PGD, or to consider different repair strategies for Damage State 4 if it is caused primarily by PGD instead of ground shaking, the model includes separate tables for defining post-earthquake traffic states for Damage State 4 due to PGD vs. ground shaking.

5.4.2.3 Damage States and Associated Repair Consequences and Strategies

Table 5-9 describes the general repair consequences and strategies that are assumed for each of the HAZUS99-SR2 damage states.

Table 5-9. Assumed Bridge Repair Consequences and Strategies

Damage State (FEMA, 2002)	Repair Consequences and Strategies
1 (None)	No repair costs or interruption of traffic.
2 (Slight)	Minor repair costs but no shoring is needed. No interruption of traffic.
3 (Moderate)	Bridge damage is repairable, but shoring will be needed before repairs proceed. Shoring must be sufficient to totally support all dead loads and full traffic loads during repairs. Any jacking/ramping needed at locations of moderate settlement and offset will be done while shoring is proceeding. Bridge will be fully closed to traffic during shoring, and then fully reopened to traffic while repairs proceed. Moderate repair costs will be incurred.
4 (Extensive)	Some bridge elements are irreparably damaged and must be replaced. However, replacement of these elements can occur without replacing entire bridge. Bridge will first be extensively shored so that all dead loads and full pre-earthquake traffic loads are completely supported during replacement of damaged elements. Any jacking or ramping needed at locations of significant offset or settlement will be done while shoring is proceeding. Bridge will be fully closed to traffic during shoring, and then fully reopened to traffic during replacement of damaged elements. Major costs for replacement of damaged elements will be incurred. The shoring requirements for extensively damaged bridges will be more extensive than the shoring for moderately damaged bridges.
5 (Complete)	Irreparable damage is sufficiently extensive to require replacement of entire bridge.

5.4.2.4 Repair Resources

If an earthquake causes major damage to many elements of the region's infrastructure (e.g., to its buildings, power systems, and other lifelines), there could be competition for repair resources, particularly if such resources are scarce. However, this bridge repair model assumes that Caltrans will have rapid access to sufficient equipment, labor, and material resources so that shoring and repair of all damaged bridges can proceed without undue delays. These resources may be available within Caltrans, and/or through outside on-call contractors who can be rapidly mobilized to initiate the bridge repairs. If such resources are not available, the REDARS™ 2 user should adjust this default repair model.

5.4.2.5 Accessibility of Bridge Damage

It is assumed that all elements of the damaged bridges will be accessible for repairs. For any bridges that cross major rivers or have other accessibility constraints, the repair costs, durations, and traffic states provided in this default model could underestimate actual repair requirements. For such bridges, this default repair model should be overridden by the user.

5.4.2.6 Underlying Roadways

If a damaged bridge crosses over an underlying roadway, this default bridge repair model accounts for possible effects of this damage on traffic along that roadway. In this model, it is assumed that there is sufficient clearance along and between the underlying roadways so that shoring of the overlying damaged bridge will not extend into the lanes of these roadways. As a result, once the overlying bridge is shored, the traffic along the underlying roadways will be fully open to traffic.

5.4.2.7 Non-Roadway Infrastructure

Experience from past earthquakes has shown that traffic along bridges can be affected by damage to adjacent buildings and to co-located power, water, wastewater, natural gas, and communications pipelines or conduits. Effects of such damage on post-earthquake traffic states along the bridges are neglected in this default repair model.

5.4.2.8 Emergency Repairs

After the Northridge Earthquake, Caltrans implemented an emergency strategy for rapid replacement of certain collapsed bridges along freeways that were vital to the recovery of the Los Angeles area. This strategy consisted of a bonus-incentive program for the construction contractors that increased replacement costs but substantially reduced repair times (thereby accelerating the time for restoration of normal traffic operations along these freeways).

The repair costs and durations provided in this default model are assumed to apply for non-emergency repairs only. If it is decided to carry out the above emergency strategy for any bridge, the user can assume that the bridge replacement costs are doubled relative to those estimated in this default repair model, and the repair durations are cut in half.

5.4.3 Repair Model Implementation

Application of the default bridge repair model that is based on the above assumptions allows the user to carry out different estimates of traffic states due to damage from ground shaking and PGD, and then use the most severe of these estimates as the bridge's governing traffic state. REDARS™ 2 does not currently accommodate separate estimates of repair costs from damage due to ground shaking and ground displacement. Such upgrades will be considered as a future improvement to the REDARS™ 2 software, along with the parallel development of improved models for estimating bridge damage states as a function of PGD.

5.4.3.1 Step 1: Estimate Traffic States during Repair of Damage from Ground Shaking and Ground Displacement

After the bridge's damage state from ground shaking hazards is estimated as described in Section G.2 of Werner et al. (2006), Table 5-10 is used to estimate the traffic state of the bridge and its underlying roadway (if any) while initial inspection, shoring, mobilization and repairs are proceeding..

Table 5-10. Default Traffic States during Repair of Bridge Damage from Ground Motions

Bridge Damage State (FEMA, 2002)	Number of Bridge Spans	Post-Earthquake Traffic State: Bridge		Post-Earthquake (EQ) Traffic State: Underlying Roadway	
		Time after EQ, days	Percent of Pre-EQ Traffic-Carrying Capacity	Time after EQ, days	Percent of Pre-EQ Traffic-Carrying Capacity
None or Slight	--	0 days	100%	0 days	100%
Moderate	--	0-4 days	0%	0-4 days	0%
		> 4 days	100%	> 4 days	100%
Extensive	--	0-12 days	0%	0-12 days	0%
		> 12 days	100%	> 12 days	100%
Collapse:	3 spans	0-140 days	0%	0-30 days	0%
		> 140 days	100%	> 30 days	100%
	4 spans	0-180 days	0%	0-30 days	0%
		> 180 days	100%	> 30 days	100%
	≥ 5 spans	0-220 days	0%	0-30 days	0%
		> 220 days	100%	> 30 days	100%

In addition, after the bridge's damage state due to ground displacement is estimated as described in Section G.3 of Werner et al. (2006), Table 5-11 is used to estimate the traffic state of the bridge and its underlying roadway (if any) at various times after the earthquake. If the bridge's estimated traffic state due to damage from ground shaking and ground displacement are different at any post-earthquake time, REDARS™ 2 will assume that the most severe of these traffic states will govern.

It is noted that the default traffic state estimates provided in Tables 5-10 and 5-11 do not consider partial bridge traffic-carrying capacity. That is, bridge is assumed to be either fully closed to traffic or fully closed to traffic at all times from the time of the occurrence of the earthquake to the time when the bridge is 100% repaired. However, these estimates can be overridden by the user, during which the possibility of the bridge being reopened to partial traffic at any time during the repairs can be considered. For this situation, Table 5-12 represents a default definition of a partially reopened bridge as a function of the number of bridge spans. This reopened bridge definition can also be modified by the user if desired.

Table 5-11. Default Traffic States during Repair of Bridge Damage from Permanent Ground Displacement

Bridge Damage State (FEMA, 2002)	Number of Bridge Spans	Post-Earthquake Traffic State: Bridge		Post-Earthquake (EQ) Traffic State: Underlying Roadway	
		Time after EQ, days	Percent of Pre-EQ Traffic-Carrying Capacity	Time after EQ, days	Percent of Pre-EQ Traffic-Carrying Capacity
None or Slight	--	--	--	--	--
Moderate	--	--	--	--	--
		--	--	--	--
Extensive	--	0-12 days	0%	0-12 days	0%
		> 12 days	100%	> 12 days	100%
Collapse:	3 spans	0-140 days	0%	0-30 days	0%
		> 140 days	100%	> 30 days	100%
	4 spans	0-180 days	0%	0-30 days	0%
		> 180 days	100%	> 30 days	100%
	≥ 5 spans	0-220 days	0%	0-30 days	0%
		> 220 days	100%	> 30 days	100%

Table 5-12. Default Definition of "Partially Opened" Bridge

Bridge Damage State (FEMA, 2002)	Number of Lanes Each Way Open to Traffic after Earthquake					
	Pre-EQ Lanes = 1	Pre-EQ Lanes = 2	Pre-EQ Lanes = 3	Pre-EQ Lanes = 4	Pre-EQ Lanes = 5	Pre-EQ Lanes = 6
None	1	2	3	4	5	6
Slight	1	2	3	4	5	6
Moderate	0	1	2	3	4	5
Extensive	0	1	1	2	2	2
Collapse	0	0	0	0	0	0

5.4.3.2 Step 2: Estimate Bridge Repair Cost

In this repair model, the repair cost is computed as the product of a repair cost ratio (*RCR*) which depends on the bridge's damage state, and the replacement cost, which depends on the bridge's surface area. Table 5-13 provides default values for the *RCR*s and the bridge's unit replacement costs, which can be overridden by the user. The most severe of the damage states estimated for this bridge due to ground shaking and PGD is used as the damage state in this table.

Table 5-13. Default Bridge Repair Costs

Damage State Designation	Best Estimate Repair-Cost Ratio (*RCR*)[1, 2]
None	*RCR* = 0.0
Slight	*RCR* = 0.03
Moderate	*RCR* = 0.25
Extensive	*RCR* = 0.75
Collapse	*RCR* = 1.0

1 Repair-Cost Ratio (*RCR*) is equal to the ratio of the repair cost for each damage state to the replacement cost.

2 Bridge replacement cost *(REP)* is computed as the product of a unit replacement costs (in dollars/ft^2) and the surface area of the bridge in ft^2 (defined as the product of the total bridge's length and its width.) The default replacement cost in this repair model is assumed to be \$150/ft^2, which corresponds to data provided by Caltrans for a typical cast-in-place prestressed-concrete box-girder bridge in Northern California. However, since this replacement cost may differ for other materials of construction and for other regions of the country, REDARS™ 2 is structured to enable users to override this default replacement cost for any bridge in the system. The above default *RCR* values can be readily overridden for any bridge.

5.5 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.

Although approach fill settlement does not typically require extensive repair costs and times, it is the most commonly-occurring type of roadway-system damage that has been observed during recent earthquakes in the United States. Therefore, default models for estimating approach-fill settlements and corresponding damage states, traffic states, and repair costs have been included in REDARS™ 2.

5.5.1 <u>Estimation of Approach Fill Settlement</u>

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

5.5.1.1 Input Data

Two sets of input data are required to estimate approach fill settlement. These consist of bridge-dependent data and earthquake- and simulation-dependent data.

5.5.1.1.1 Bridge-Dependent Data

The bridge-dependent data needed to estimate approach fill settlement consist of: (a) the bridge number and location within the highway system; (b) the relative compaction of the approach fill soils (standard Procter density) (RC); and (c) the maximum thickness of the approach fill (T_{AF}).

The bridge number and location are specified as part of the input provided by the Import Wizard (see Appendix B). Also, in the absence of actual RC and T_{AF} data at a bridge site, the following default values of these parameters are included in REDARS™ 2: (a) RC = 95%; and (b) T_{AF} = 12 ft. (see Figure 5-11). These default values for any bridge in the system can be overridden by REDARS™ 2 users.

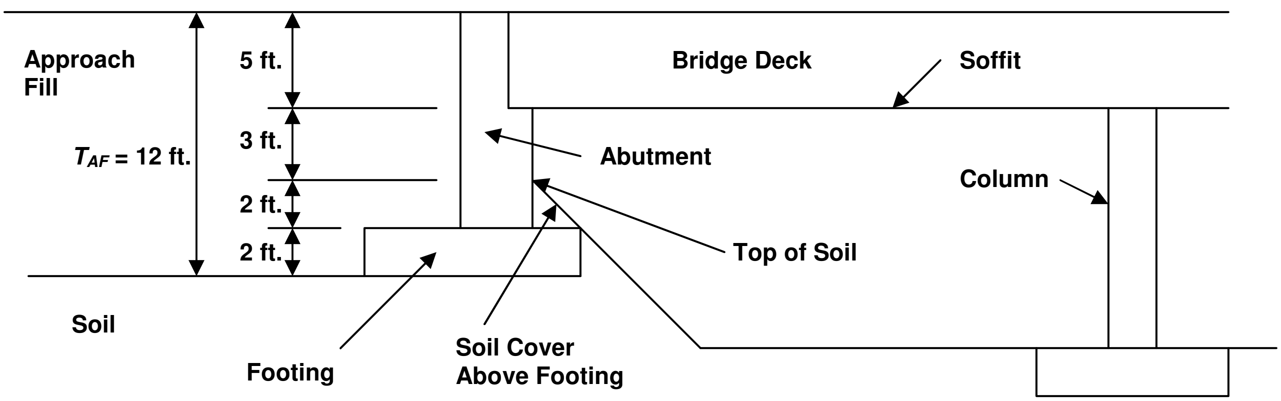


Figure 5-11. Estimation of Default Value of Approach Fill Thickness

5.5.1.1.2 Earthquake- and Simulation-Dependent Data

The earthquake- and simulation-dependent data needed to compute approach-fill settlement are: (a) the moment magnitude of the earthquake (M_w); and (b) the peak ground acceleration at the bridge site (PGA). The moment magnitude is obtained from the scenario earthquake designation, and the PGA is computed for each scenario earthquake and simulation, using the REDARS™ 2 ground motion model that is being used for this analysis.

5.5.1.2 Evaluation Procedure

The evaluation of approach fill settlement for each bridge, scenario earthquake, and simulation consists of the following steps:

- For the earthquake's M_w, and the site-specific PGA for the simulation, and the RC of the approach fills, use Table 5-13 to estimate the volumetric strain of these fills (ε_{AF}) .

- Compute the total settlement of the approach fill (S_{AF}) as:

$$S_{AF} = \varepsilon_{AF} T_{AF} \tag{5-5}$$

5.5.2 Damage States, Repair Costs, and Traffic States

This section describes the REDARS™ 2 default model for estimation of approach-fill repair costs and downtimes due to earthquake-induced approach-fill settlement. This default model was developed from collaboration with and recommendations by senior members of the Caltrans engineering staff. Therefore, the model is applicable to approach-fill construction and repair practices in California only. Since these practices may differ in other regions of the country where REDARS™ 2 may be applied, this default model may require modification by users from these other regions to reflect any differences in these practices.

Table 5-13. Best-Estimate Value of Maximum Volumetric Strain in Dry Soil due to Seismic Shaking (Youd, 2002)

Scenario Earthquake and Simulation Data		Volumetric Strain (%)		
Earthquake Magnitude (M_w)	Peak Ground Acceleration (PGA), (g)*	Loose Fill (RC < 90%)	Moderately Dense Fill (90% ≤ RC < 95%)	Dense Fill (RC ≥ 95%)
$M_w \geq 7.0$	PGA ≥ 0.4 g	10%	5%	1%
	0.2 g < PGA < 0.4 g	5%	2%	0.5%
	0.1 g < PGA ≤ 0.2 g	2%	0.5%	0.1%
$5.0 < M_w < 7.0$	PGA ≥ 0.4 g	6%	3%	0.5%
	0.2 g < PGA < 0.4 g	2%	1%	0.2%
	0.1 g < PGA ≤ 0.2 g	1%	0.2%	0.05%
Mw ≤ 5.0	PGA ≥ 0.4 g	3%	1%	0.2%
	0.2 g < PGA < 0.4 g	1%	0.2%	0.05%
	0.1 g < PGA ≤ 0.2 g	0.5%	0.1%	0.01%

* In REDARS™ 2, it is assumed that no approach fill settlement will occur if PGA < 0.1 g.

5.5.2.1 Approach Slab Configuration and Design

California approach slabs consist of a 30-ft. long by 1-ft. thick reinforced concrete slab that is underlain by a 6-inch thick permeable base. Soils beneath the concrete slab and permeable base consist of granular fills that are compacted to 95% Procter density.

In California, the reinforced concrete approach slab is designed to function as a simply-supported bridge. Therefore, if part of the underlying soil settles away from the slab and creates a void, the slab will still be able to function structurally and support traffic loads. Because of this, all bridges along lifeline routes in California have approach slabs.

5.5.2.2 Replacement Costs

In REDARS™ 2, repair costs for all components are specified as multiples of replacement cost. For approach fills, this replacement cost is estimated from the following assumptions:

- The cost to replace an approach slab in California is about $13,000/lane (where a lane is typically 12 ft. wide.) This would involve removing the existing slab, constructing a paving notch (if needed), leveling the subgrade with aggregate base, constructing the new slab, and replacing the joint seal. Since this work would be carried out under an emergency contract rather than formal bid, these costs include appropriate markups for CCO. Costs for mobilization (usually about 10 percent) or contingencies are excluded from this estimate.

- If an approach slab were sufficiently damaged to require replacement, it is probable that the underlying fills will require some compaction and new fills would need to be added. Unit costs for this fill compaction/addition are estimated to be about \$100/m^3. If it is conservatively assumed that the total volume of fill to be compacted/added for each lane of roadway will be equal to the total slab length (30-ft.) x the lane width (12-ft) x the approach fill settlement, this cost is about $1,000/lane/(ft.-of-approach-fill-settlement). For a bridge that has settled 1.5-ft. (which is an upper-bound settlement for soils with a 95% compaction), this works out to be about $1,500/lane. Thus, the total cost to replace the approach slab and to add/compact the underlying fill is assumed to be $14,500/lane. For a 30-ft approach slab and a 12-ft. lane, this turns out to be about \$434/m^2.

5.5.2.3 Repair Costs

In this model, repairs are defined for three different levels of approach-fill settlement: (a) more than 6 in.); (b) between 0.083 ft. (1 in.) and 0.5 ft. (6 in.), and (c) less than 0.083 ft. (1 in.). It is noted that none of these levels of settlement are considered to lead to replacement of the approach slab. This is because, as noted above, the approach slabs are designed to bridge over settled fills and continue to accommodate traffic loads.

- If an approach slab has settled more than 0.5 ft., temporary repairs would involve building up an asphalt concrete (AC) ramp. Under emergency conditions, this will require total closure of the bridge for about 4 days, after which full traffic can be accommodated. The total unit cost to repair the 1-ft. thick structural slab and the underlying 0.5-ft. thick permeable base will be $600/m^3 and $350/m^3 respectively. This works out to be $6,117/lane for repair of the structural slab and $1,784/lane for repair of the underlying base, which amounts to a total cost of about $7,900/lane, or about 0.55 x the above unit replacement cost,

- If an approach slab has settled less than about 0.5-ft. but more than about 0.083 ft., repairs will consist of mud jacking (coring holes and pumping in grout) and then ramping up with AC. Repair costs for this process will be about $50/m^2 which, for a 30-ft long approach slab and a 12-ft. lane width, works out to be about $1,700/lane, or about 0.12 x the above unit replacement cost.

- REDARS™ 2 uses the following algorithm to estimate a default number of approach fills for any given bridge, as a function of the number of bridge elements and roadway elements immediately adjacent to the bridge in the roadway network model:
  - If the elements on both sides of the bridge are roadways, the bridge is assumed to have two approach fills – one at each end of the bridge.
  - In REDARS™ 2, an elevated viaduct of extended length will be modeled as a series of bridges connected end to end. For a bridge in this series that is connected to a roadway element on one side and to a bridge element on the other side, the bridge is assumed to have one approach fill only. For a bridge in this series that is connected to a bridge element on both sides, the bridge is assumed to have no approach fills.

5.5.2.4 Default Repair Model

Based on the above assumptions, the REDARS™ 2 default repair model for approach slabs is shown in Table 5-14. This table provides repair procedures, post-earthquake traffic states, and repair costs as a function of approach fill settlement.

5.6 DEFAULT MODEL FOR ROADWAY PAVEMENTS

5.6.1 Model Basis and Assumptions

The REDARS™ 2 default model for roadway pavements is based on the judgment and recommendations of senior Caltrans staff members who are familiar with pavement construction, maintenance, and repair practice in California. This should be regarded as a first-order model that may be upgraded in the future, as further experience and data regarding the seismic performance of pavements are developed. The model does not differentiate between concrete and asphalt pavements.

This default model will characterize the seismic performance and associated repair costs and post-earthquake traffic states for pavements. Since it is a default model, it can be readily modified by REDARS™ 2 users. In particular, since this model is based on pavement construction and repair practices in California, it may not apply to pavements in other regions of the country where construction and repair procedures and resources may differ from those in California. REDARS™ 2 users from these other regions should modify this model as needed to best reflect their particular construction and repair practices.

Table 5-14. Post-Earthquake Traffic States and Repair Costs due to Approach Fill Settlement

Damage State		Repair Procedure	Traffic State		Repair Cost (fraction of replacement cost)*
REDARS™ Designation	Approach Fill Settlement, in.		Day after EQ	Traffic Capacity (fraction of Pre-EQ Capacity)	
1	≤ 0.083 ft. (1.0 in.)	No repairs needed.	0	1.00	0.00
2	between 0.083 ft. (1.0 in.) and 0.5 ft. (6.0 in.)	Closed for 1 day for during inspection and mobilization. Repair consists of mud jacking (coring holes and pumping in grout) and then ramping up with A/C. Repairs during off hours.	0-1 days > 1 day	0.00 1.00	0.12
3	≥ 0.5 ft. (6.0 in.)	Closed for one day for inspection and mobilization. Temporary repairs involve building up an A/C ramp, and will require closure of bridge for additional three days. Subsequent permanent repairs done during off hours. (Assuming only small-moderate settlement and no fault rupture.)	0-4 days ≥ 5 days	0.00 1.00	0.55

*Replacement Cost assumed to be $14,500/lane which, for an approach that is 30 ft. long and has lanes that are 12 ft. wide, works out to be about $434/m^2.

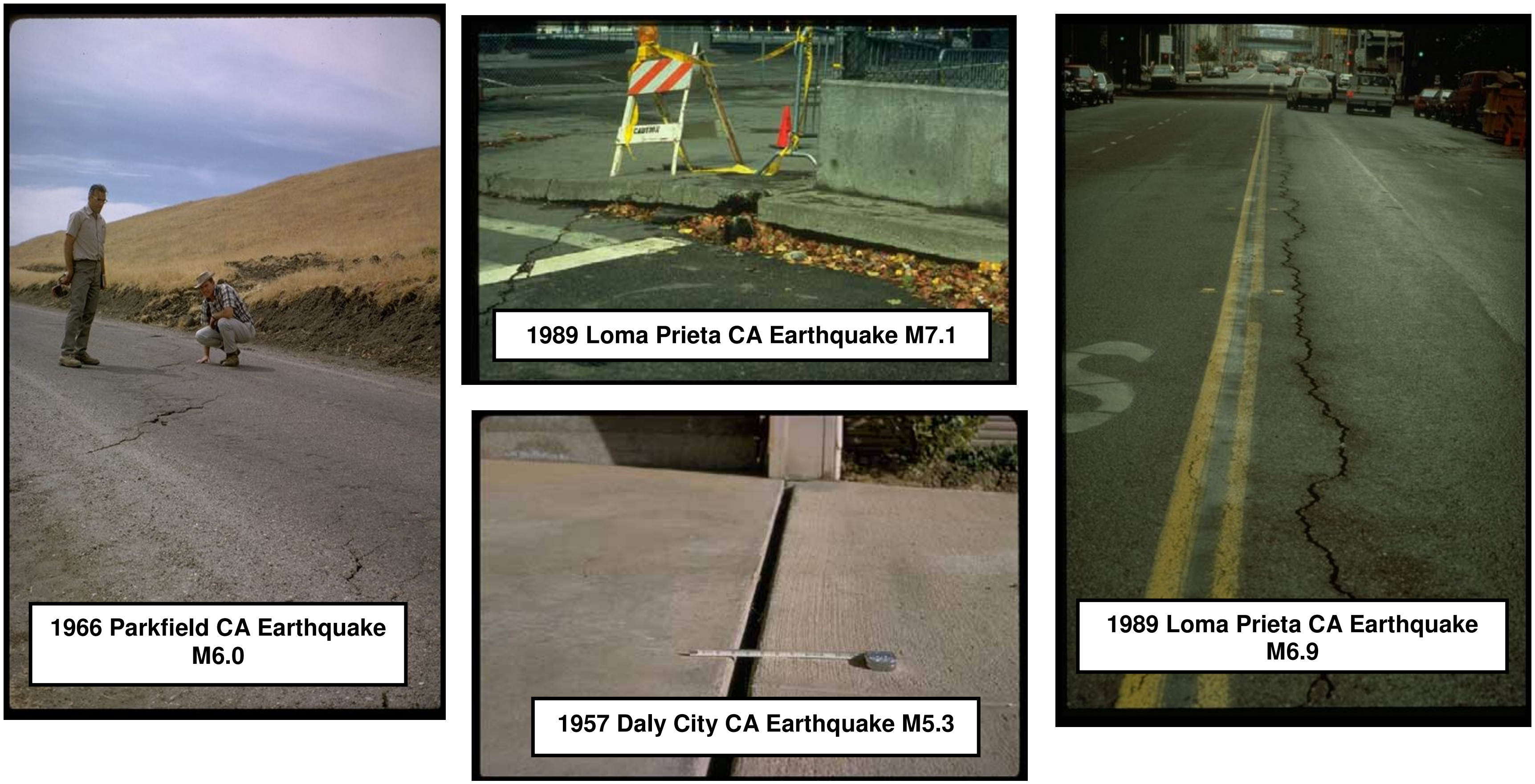
5.6.2 Use of Model in REDARS™ 2

For each scenario earthquake and simulation being analyzed, REDARS™ 2 estimates the PGD along each link within the roadway system that is located in potentially liquefiable soils or in the zone of deformation of the causative fault. Then, for each of these links, the model described in this section will estimate the corresponding damage state and the associated repair cost, duration, and traffic state. If a link is not located within the rupture zone for the causative fault and is not sited on potentially liquefiable soils, REDARS™ 2 will not compute PGD hazards or estimate PGD-induced pavement damage states and repair requirements. Table 5-15 shows this default roadway pavement model, and the pavement damage states on which this repair model is based are illustrated in Figures 5-12 through 5-15.

Table 5-15. Default Earthquake Damage and Repair Model for Roadway Pavements and Subsurface Materials

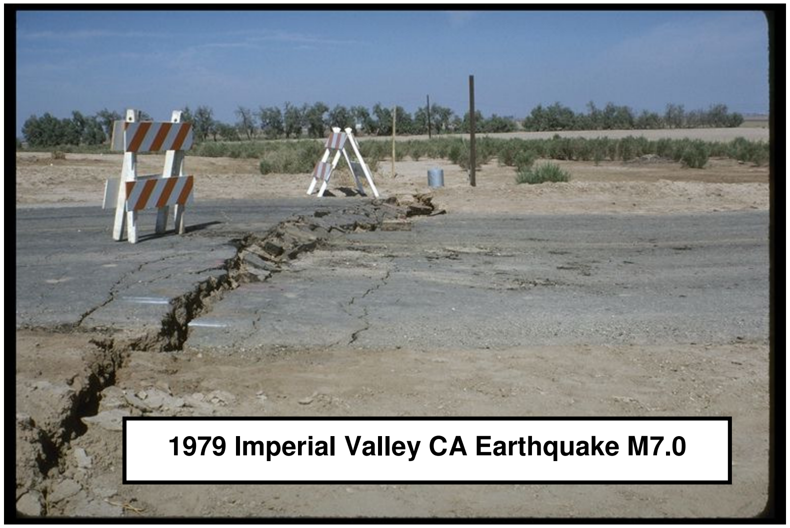
Damage State				Traffic State		Repair Costs (per lane-mile)
REDARS™ Designation	Perm. Ground Displacement, inches.	Description (see Figures 1 through 4)	Repair Procedure	Days after EQ (incl. mobilization time)	Lanes Available (% of Pre-EQ lanes)	
1 (None)	< 1 in.	No repairs needed	None	0	100%	$0
2 (Slight)	≤ 1 in and <3 in.	Slight cracking/ movement. No interruption of traffic.	Horizontal Displacement: crack/seal. Vertical Displace: mill and patch.	0	100%	$50,000 (=0.083*RC)
3 (Moderate)	≤ 3 in and <6 in.	Localized moderate cracking/ movement. Reduced structural integrity of pavement surface.	No repair needed for subbase. If asphalt pavement, or if damage to concrete pavement extends over long length, use AC overlay. If damage to concrete pavement is localized, replace concrete slab.	0-3 days ≥ 4 days	0% 100%	$100,000 (=0.167*RC)
4 (Extensive)	≤ 6 in and <12 in.	Failure of pavement structure, requiring replacement. Movement but not failure of subsurface soils.	Rebuild pavement structure and subbase. Provide soil improvement for subsurface materials.	0-7 days ≥8 days	0% 100%	$300,000 (=0.500*RC)
5 (Irreparable)	≥ 12 in.	Failure of pavement structure and subsurface soils.	Remove and replace existing pavement structure and subsurface materials.	0 – 49 days ≥ 50 days	0% 100%	$600,000 (=RC)

Figure 5-12. Examples of Category 2 Roadway Damage
(Description: No closure to traffic. Minor repairs can be carried out during off hours)



All photographs courtesy of Earthquake Engineering Research Center Library, University of California at Berkeley, Richmond CA.

Figure 5-13. Examples of Category 3 Roadway Damage
(Description: Closure to Traffic for 2-3 Days for Repair of Moderate Pavement Damage. No Subbase Damage)


1979 Imperial Valley CA Earthquake M7.0


1971 San Fernando CA Earthquake M6.4


1999 Izmit Turkey Earthquake M7.4


1989 Loma Prieta CA Earthquake M6.9

Figu

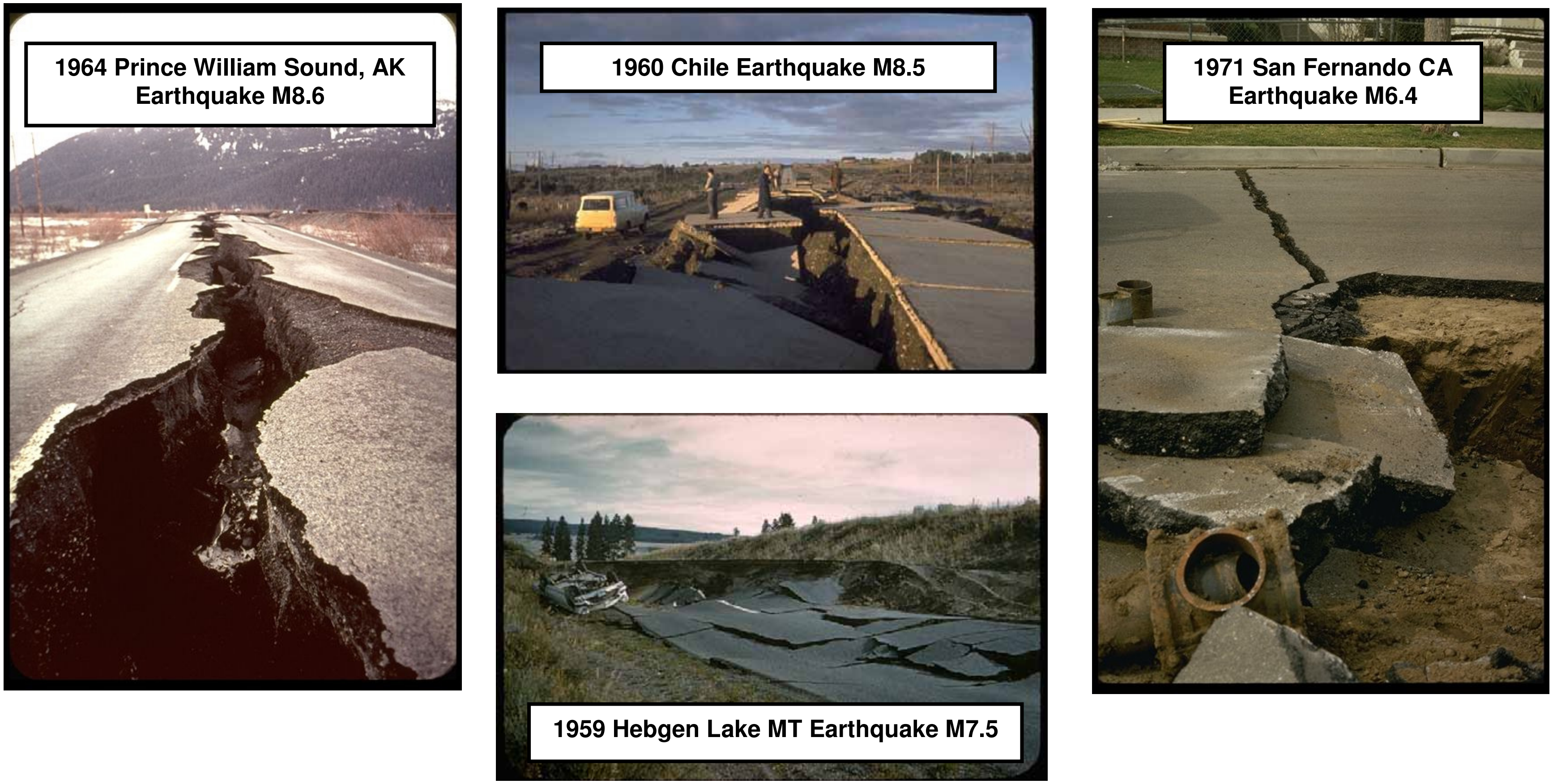
All photographs courtesy of Earthquake Engineering Research Center Library, University of California at Berkeley, Richmond CA.

Figure 5-14. Examples of Category 4 Roadway Damage
(Description: Pavement Structure has Failed (must be Rebuilt) and Soils have Deformed (Closure for 7 Days)

Fig

All photographs courtesy of Earthquake Engineering Research Center Library, University of California at Berkeley, Richmond CA.

Figure 5-15 Examples of Category 5 Roadway Damage
(Description: Total Failure Requiring Reconstruction of Pavement and Underlying Soils (Closure for 7 Weeks)



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CHAPTER 6
TASK 4: UPDATED SYSTEM MODULE FOR CALIFORNIA APPLICATIONS

6.1 OBJECTIVE

Under Task 4, the RDT updated the REDARS™ 2 network model to: (a) enable trip demands to be responsive to network delays caused by earthquake-induced damage and reduced network capacity; and (b) enable it to accommodate multiple trip types, within which trips that transport various types of freight with have their own unique origins and destinations as well as economic values that will differ from those for passenger trips. This chapter describes these model upgrades, as well as an additional upgrade in which a minimum-path algorithm that substantially reduces computation time has been incorporated into the model

6.2 OVERVIEW

As described in Werner et. al. (2000), the first SRA applications using a forerunner of the current REDARS™ 2 software (termed REDARS™ beta) included a network-analysis procedure that was based on the following models and 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. The user-equilibrium model is widely used in current transportation-analysis practice.
- ***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 travel demand on the highway system would not be affected by this increased congestion.
- ***One Trip Type.*** All traffic is represented by a single origin-destination (O-D) 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 user-equilibrium model with variable-demand that accounts for the effects of traffic congestion.
- ***Dual-Simplex Minimum-Path Algorithm.*** A more efficient dual-simplex algorithm for searching all-to-all paths, as detailed by Florian, et. al. (1981), has been incorporated.
- ***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.

6.3 VARIABLE-DEMAND MODEL

6.3.1 Statement of the Problem

The fixed-demand user equilibrium model (FDM) that was included in prior versions of REDARS™ is widely used in transportation network-analysis. However, preliminary results from a recent validation of this model based on observed traffic flows after the Northridge Earthquake indicates that, although the FDM model is adequate for region-wide transportation planning, it does not provide adequate estimates of traffic along damaged highways or links. For example, according to local traffic reports obtained one day after the earthquake (Caltrans, 1995), observed traffic volume 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 extreme conditions, the observed travel-times along these roads increased by only 15 minutes per trip relative to the pre-earthquake travel time. However, when the FDM 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.

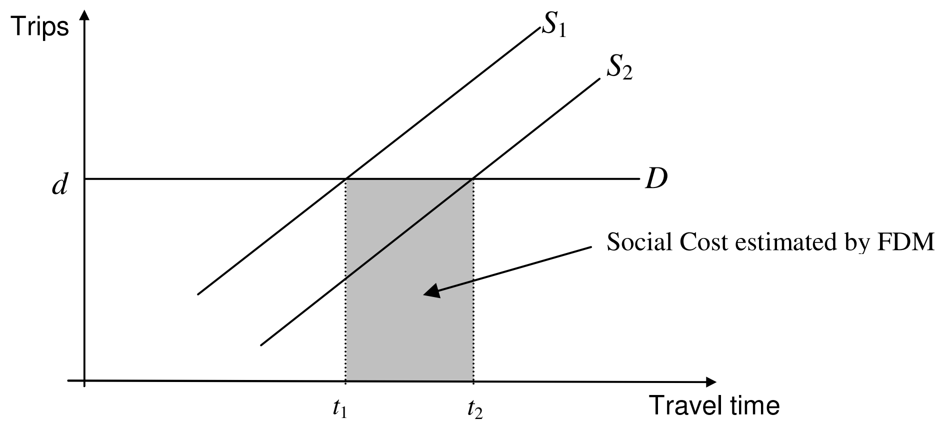
One reason for this result is that the FDM model assumes that the trip demand is inelastic (i.e., fixed). However, this assumption is not plausible under conditions of substantially reduced network capacity and corresponding increased traffic congestion. Under these conditions, observed data has shown 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 user equilibrium model (VDM) for network analysis that replaces the fixed-demand user-equilibrium model. This model is summarized below, and is further described and illustrated in Sections C.2 through C.5 of Appendix C.

6.3.2 Model Development

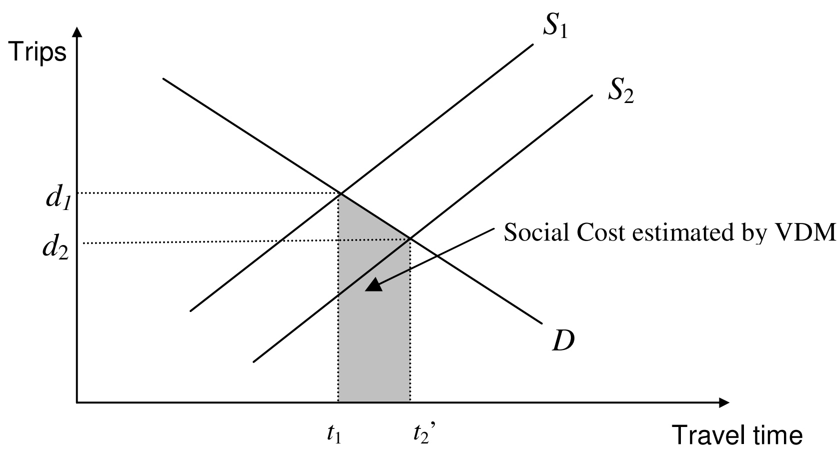
This section summarizes the REDARS™ methodology for calculating the economic impacts of earthquake-induced traffic disruption using: a) zone-to-zone trip demands; and b) the corresponding change in travel time estimated by the VDM. The economic impacts include the value of time due to increased traveler time on the roadway, and the value of trips foregone. REDARS™ calculates them separately for each trip type, and reports the sum for social cost.

The FDM model 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 will proceed with their trip, even if it requires an unreasonably long travel time. Figure 6-1a illustrates this situation following a damaging earthquake that reduces the system's traffic-carrying capacity and increases traffic congestion. For this case, the network capacity (or supply) is reduced from S_1 to S_2, and the fixed trip demand is represented by $d = D$.[1] The corresponding travel times are t_1 and t_2 respectively, and the social cost is $(t_2 - t_1) \cdot d$.

[1] Note that, in Figure 6-1, the axes are reversed for consistency with subsequent examples.



a) User-Equilibrium Model with Inelastic (Fixed) Demand (FDM) for Earthquake-Damaged Network



b) User-Equilibrium Model with Elastic (Variable) Demand (VDM) for Earthquake-Damaged Network

Figure 6-1: Social Cost Predictions by User-Equilibrium and Variable-Demand Models

The assumption that travel demand remains constant is not appropriate for the analysis of a highway-roadway 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 their 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 6-1b illustrates the resulting effects of elastic trip demand, *D*, as characterized by the VDM. This figure shows that before an earthquake, the transportation system would provide a capacity of S_1, and the travel demand on this network, $d_1 = D(t_1)$, would result in an equilibrium travel time of t_1. After an earthquake, the capacity would be reduced to S_2, which would lead to a reduced travel demand, d_2, and a travel time, t_2', that is increased relative to the pre-earthquake travel time t_1. The resulting social cost of this reduction in network capacity is given by the expression $[(t_2'-t_1)\cdot d_2]+[(t_2'-t_1)\cdot(d_1-d_2)/2]$, and will be much lower than the cost predicted by the UEM.

6.3.3 Mathematical Form of Variable Demand Model

The VDM was developed to estimate link volumes, link travel times, and travel demands that satisfy the equilibrium conditions. At equilibrium, the travel time on all used paths between any origin-destination (O-D) pair are equal and are less than the travel times on any usused paths. In addition, trip rates between an origin and a destination are consistent with travel time, as calculated by a given demand function. These conditions define the VDM whose mathematical form is as follows:

$$\min\ Z(x,d)=\sum_a \int_0^{x_a} t_a(w)dw-\sum_{rs}\int_0^{d_{rs}} D_{rs}^{-1}(w)dw \qquad (6\text{-}1)$$

subject to

$$\sum_k f_k^{rs}=d_{rs} \qquad \forall r,s \qquad (6\text{-}2)$$

$$f_k^{rs}\geq 0 \qquad \forall k,\ r,s \qquad (6\text{-}3)$$

$$d_{rs}\geq 0 \qquad \forall r,s \qquad (6\text{-}4)$$

$$d_{rs}=D_{rs}(t_{rs}) \qquad \forall r,s \qquad (6\text{-}5)$$

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

where

Z	the object function of VDM, whose solutions satisfy the equilibrium conditions
t_a	link performance function of link *a*.
D , D^{-1}	demand function and its inverse (see Section 6.2.4 for details)
f_k^{rs}	flow on path *k* connecting OD pair *r-s*.
d_{rs}	trip rate between OD pair *r-s*.
t_{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.

The first term on the right side of Equation 6-1 represents link volumes and travel times that satisfy the FDM. The second term adjusts travel-demand rates between zone pairs such that the loaded travel demand on the network is consistent with its travel time. The procedure used in REDARS™ 2 to solve this system of equations is described in Section C.2 of Appendix C.

6.3.4 Calibrating the Demand Function

Equations 6-1 through 6-6 represent the situation wherein a demand function, *D* actually reduces trips according to the network capacity and associated travel time estimated in VDM. However, in current transportation planning processes, travel demand is assumed to be fixed according to origin-destination-specific parameters that reflect region-specific population sizes, income distributions, and vehicle ownerships by origin zone, as well as employment statistics and retail-activity. As a result of this region-specific data dependency, no universal demand function is available that is usable for the VDM in REDARS™2. Therefore, the REDARS™ 2 Import Wizard calibrates the demand function as it creates the input database for the study region, based on given O-D matrices and a fixed network capacity. This calibration procedure 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. 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. 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 Import Wizard assumes that the relationship between trip rate and travel time follows the simple form shown in Figure 6-2.

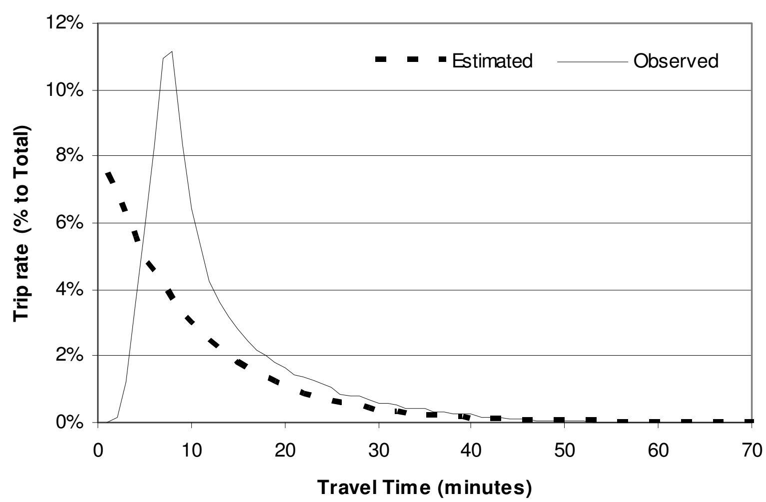


Figure 6-2: Real Trip Rate and Estimated Demand Function

On the basis, the demand function to be calibrated is assumed to have the following functional form:

$$d_{rs} = P_r \cdot A_s \cdot c_r \cdot d_s \cdot \exp(\alpha + \beta \cdot t_{rs}) \tag{6-7}$$

where

d_{rs}	baseline trips between zone *r* and *s* (same as the OD matrix),
t_{rs}	travel time between zone *r* and *s* (estimated by the FDM),
P_r	baseline trip production from zone *r* (aggregated from OD matrix),
A_s	baseline trip attraction to zone *s* (aggregated from OD matrix),
c_r, d_s	zone-specific parameters (estimated by the Import Wizard), and
α, β	travel time parameters (estimate by the Import Wizard).

and the term $\exp(\alpha + \beta \cdot t_{rs})$ in Equation 6-7 represents the assumed demand function that is shown by dotted line in Figure 6-2.

To develop numerical values of the various parameters in Equation 6-7, parameters that characterize trip production, P_r, and trip attraction, A_s, are obtained from the baseline O-D matrices. Then, before creating a subset network, the Import Wizard uses the FDM to analyze the network for the entire TAZ area as represented in the region-wide TAZ map provided by the Metropolitan Planning Organization (MPO), in order to obtain zone-zone travel times, t_{rs} for the fixed-demand condition.

Following this, the Import Wizard uses non-linear regression between trip rate and travel time to estimate the parameters c_r, d_s, α, and β in Equation 6-7. This requires estimation of a total of $(2 \times N) + 2$ parameters from the estimated travel time and the N^2 data points in the baseline O-D matrix, where *N* is the total number of zones in the entire TAZ area. In this, the travel-time parameters α, and β represent the sensitivity of trips to increased travel time, and the zone-specific parameters c_r and d_s represent the rate of trip generation and attraction. Although these parameters can be variable in an actual situation, the VDM treats them as constant for all conditions, in accordance with the model's assumption that drivers' behavior may not be changed over a short period of time.

6.3.5 Loss-Estimation Challenges

As summarized above, the demand function is calibrated from the baseline O-D (trip-table) matrix and the estimated travel-time matrix. Consequently, the calibrated demand function explains the general relationship between reduction of trips and increases in travel-time. However, when applying the demand function within Equations 6-1 through 6-6, the resulting travel time *t*, and trips *d* are not always exactly aligned on the demand function *D*. In many cases, especially for travel-time ranges within which the number of baseline trips is very small, *d* is not always identical to *D*(*t*). These zone pairs for which very small numbers of trips occur have only a minor influence on the minimization of the objective function *Z* in Equation 6-1, whereas zone-pairs for which large numbers of trips occur have a very significant influence on the minimization of *Z*. This is the reason for the slight lack of alignment between travel times *t*, and trips *d* and the demand function *D*.

This inconsistency between *d*, *t*, and *D* complicates the VDM's calculation of social cost. As reviewed in Section 6.3.2, the social cost is represented by to the size of area underneath of the demand function, as bounded by pre-earthquake and post-earthquake travel time and trips. However, in some cases, this area is not bounded and, as a result, no explicit social-cost calculation is possible. Even though the effect of this complication on the aggregated social cost is trivial (because the demand is insignificant), the VDM nevertheless identifies individual zone-pairs with these problematic results, and adjusts their travel-time and foregone-trip calculations through a series of rules-based statements. Using following notations, the rules are listed below, along with a description of how each case is handled in REDARS™ 2.

d_1 : Pre-earthquake trips
d_2 : Post-earthquake trips
t_1 : Pre-earthquake travel timet_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% of all trips. If a zone is isolated from the network, d_2=0, and t_2= ∞. In this case the earthquake calculations are as follows.

$$C_1 = d_2 \cdot (t_2 - t_1) \tag{6-8}$$

$$C_2 = \int_{t_1}^{t_2} D(w)\, dw \quad - C_1 \tag{6-9}$$

***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 6-8 and 6-9 are applied.

6.4 UPDATE OF MINIMUM-PATH ALGORITHM

6.4.1 Background

The network analysis procedure that was applied in the prior version of REDARS™ (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. Section C.6 of Appendix C provides reduction rates for various sized network configurations.

This section describes the minimum-path algorithm that recycles path information which, in REDARS™ 2, reduces 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. The internal-memory structure of the network is also summarized, and comparisons of results using the Moore-Pape algorithm and the Dual-simplex algorithm are cited.

6.3.2 Moore-Pape Minimum-Path Algorithm

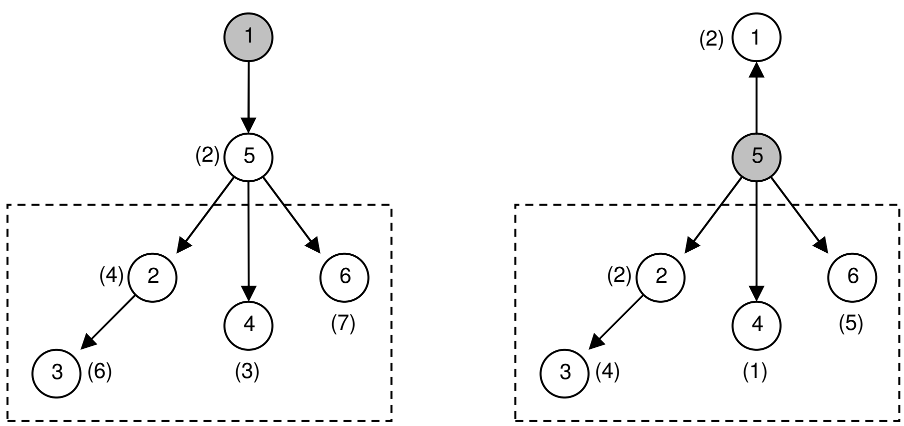
Previous versions of REDARS™ used the Moore-Pape path search algorithm adapted for transportation networks. This algorithm is particularly effective in cases where the number of nodes is much less than number of links, such as in power or communication networks. A communications switching-station, for 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. Section C.4.2 of Appendix C provides a detailed description of the minimum-path searching procedure that is based on Moore-Pape algorithm.

6.3.3 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 6-3 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 6-3 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 C.6.4 of Appendix C 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**

(travel time to the node from the root)

Figure 6-3: Comparison of Minimum Paths from Neighboring Origins

6.5 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 7
TASK 5. INPUT DATABASE NEEDS FOR CALIFORNIA APPLICATIONS

7.1 OBJECTIVE

Under Task 6, the RDT guided Caltrans' staff during their development of input data for the testbed highway system that they analyzed under Task 6, and also identified various anomalies in the available databases used by the Import Wizard to develop REDARS™ 2 input data for highway systems and for component locations and attributes

7.2 BACKGROUND

During the early stages of the development of the REDARS™ SRA methodology, it became clear that the development of input data for a SRA application by hand would be a considerable challenge that would require months of time (Werner, et al., 2000). Duirng such an effort, the user would be tasked with developing a transportation network with full topology that integrated bridges and Origin/Destination (OD) data. Therefore, as the REDARS™ prototype moved from a methodology to a fully functional software program, it was decided that, in order for the software to be at all practical to run, it would be necessary to develop a data-import module that processed standard data formats into a network database suitable for use as input to the REDARS™ 2 SRA application. This was addressed through the Import Wizard, which is software that was developed over the past few years to import data into REDARS™ 2. This Wizard is summarized in Section 3.3.1 and is further described in Appendix B of this report

A primary goal of the Import Wizard is to enable the user to create a REDARS™ 2 study region with as little effort as possible. The Import Wizard saves the end user time in both data manipulation and data acquisition. Key elements in the Wizard's automation of REDARS™ 2 data creation are FHWA databases. The data from these databases will remain relatively consistent from state to state, in regards to the format of geographical and linear referencing data, data projection, field names, field types, and data provided. Supporting and anticipating the various data formats used by state and local governments would require a much greater effort. Ideally, the user's role in creating a REDARS™ 2 study region is limited to; (a) collecting the required data from public and local sources; and (b) determining the study-region boundary.

The remainder of this chapter documents the base data collection and findings that emerged from the Caltrans beta testing of the Import Wizard. Section 7.3 explores the limitations of the Import Wizard that arise from the dependence on data provided in a standard, federally mandated format. Then, Section 7.4 summarizes the data provided for the demonstration application of REDARS™ to the East Bay Area (Richmond, Berkeley, and Oakland), along with a discussion of issues surrounding the selection of the study region. Finally, Section 7.5, discusses data problems that were identified during beta testing of the Import Wizard, and Section 7.6 provides recommendations for addressing these problems.

7.3 LIMITATIONS OF IMPORT WIZARD

The REDARS™ 2 Import Wizard uses nationally available FHWA datasets to enable prompt creation of REDARS™ 2 study regions. Although this depends on FHWA data, the actual datasets are provided by the states themselves and vary in accuracy and completeness depending on interpretation of the requirements, and completeness of the available data. These factors influence the usability of the REDARS™ study region for a given area. The following discussion explores various problems that arise in a study region due to problems with base data.

In a REDARS™ 2 study region, bridges may be missing or misplaced. This is often due to problems in the Linear Referencing System (LRS) of the base data. Frequently, state transportation agencies either do not track sub-route ID, or do so in a manor inconsistent with the National Bridge Inventory (NBI). Milepost markers are often incorrect, reversed, or in the wrong units, resulting in misplaced or omitted bridges. Possible solutions to these problems include correcting the LRS in a GIS system, or editing the original data fields to be consistent with the NBI data. These issues are examined further in Section 6.4.

The NBI, the National Highway Planning Network (NHPN) and the Highway Performance Monitoring System (HPMS) do not contain sufficient information for locating bridges that are freeway onramps. A freeform field in the NBI data does accommodate entering a general description (such as "I-10 WB to I-405 NB"), but this is rarely entered consistently enough to parse bridge location. At this time, REDARS™ 2 conservatively assumes that damaged ramps affect traffic in both freeway directions.

Attribute data in the various databases may contain incorrect or no information regarding number of lanes, link type, the rural or urban designation, and route attributes. Currently, the method to resolve these issues is to fix these problems in the base data and rerun the Import Wizard, or directly access to database to change the attribute values. Changes in base data cascade through the Import Wizard to the REDARS™ 2 study region.

The NBI primarily tracks state bridges located on freeways and highways. If detailed bridge and network data are required for analysis, users may obtain network data from their Metropolitan Planning Organization (MPO) and bridge data from the local jurisdictions or state transportation agency. These data will vary by region and are not supported by the Import Wizard. Users can create a REDARS™ 2 study region outside of the Import Wizard using the REDARS™ 2 open database format, but this would require a significant effort.

Public transit is currently not supported within REDARS™ 2. One-way routes are not distinguished in the NHPN data. Users can support one-way routes by deleting the extra directional link record in the final REDARS™ 2 study region.

7.4 DATA COLLECTION FOR CALTRANS DEMONSTRATION STUDY

7.41 Background

In establishing the testbed roadway system for Caltrans' use in this project (hereafter referred to as the Martinez Testbed system), the following criteria were used to develop the study region:

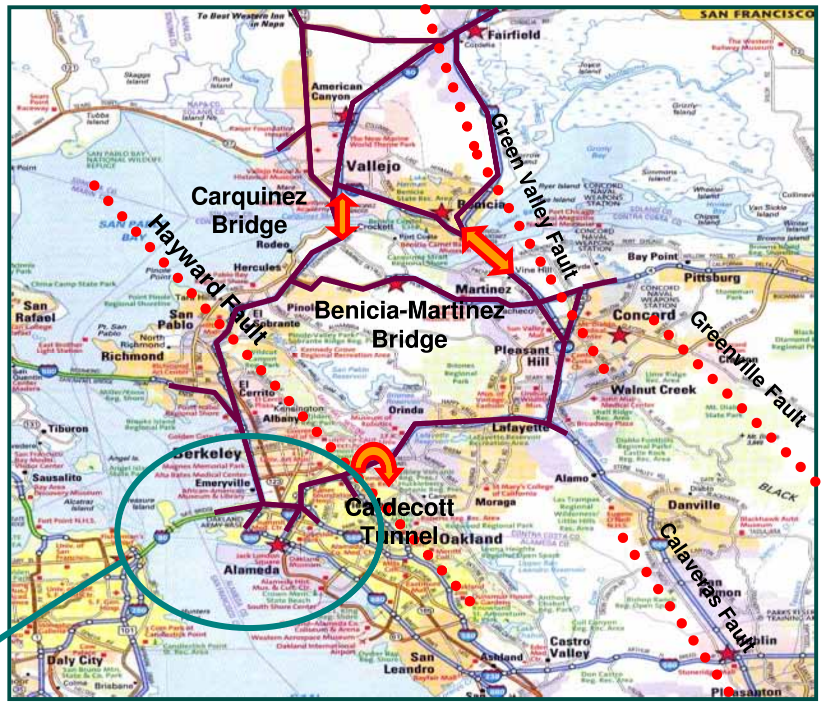
1. The region should be small enough to analyze in a reasonable time, yet large enough to consider major structures and system-wide effects. The ideal size is on the order of about 60 to 1,000 TAZs. The Martinez Testbed study region contains about 200 TAZs.
2. The study region's boundary should generally follow political boundaries, and must be a collection of TAZs. Cities or population centers should be fully included or excluded in a study region, rather than partially included. If a region is too large to analyze in its entirety, the region should surround the area of interest with a considerable buffer.
3. The study region should have a simple boundary that includes the transportation network elements that affect the system. Since the highway system within a study region will usually be a subset of a larger regional system, the network created by the Import Wizard must estimate demand external to the study region. External demand includes: (a) trips from outside the study region to the inside the region; (b) trips from inside the region to a location outside the region; and (c) trips from outside the region to another location outside the region which could travel through the study region. Representation of external demand must include the freeways used to access an area of interest.

The Martinez Testbed study region includes the area shown in Figure 7.1, which extends north from Oakland to Fairfield and west from Walnut Creek to San Rafael. The region includes the I-80, I-580, and I-880 freeways, and the Carquinez Bridge, the Benicia-Martinez Bridge, and the Caldecott Tunnel. Major earthquake faults within the study region are the Hayward Fault, the Green Valley Fault, the Greenville Fault and the Calaveras Fault.

The initial version of the Testbed study region followed a boundary between I-580 and I-880 in Oakland. However, this meant that the Oakland freeways and many major arterials between the major freeways would be bisected by the study-region boundary. In addition, the Import Wizard would need to consider traffic on I-880 as external demand, which would exclude the I-880 from inclusion in the subsequent REDARS™ 2 SRA of this region. Therefore, to eliminate these problems, the study region's boundary was adjusted to now include I-880 (Fig. 6-2). The following subsections describe the data that were collected for this adjusted study region.

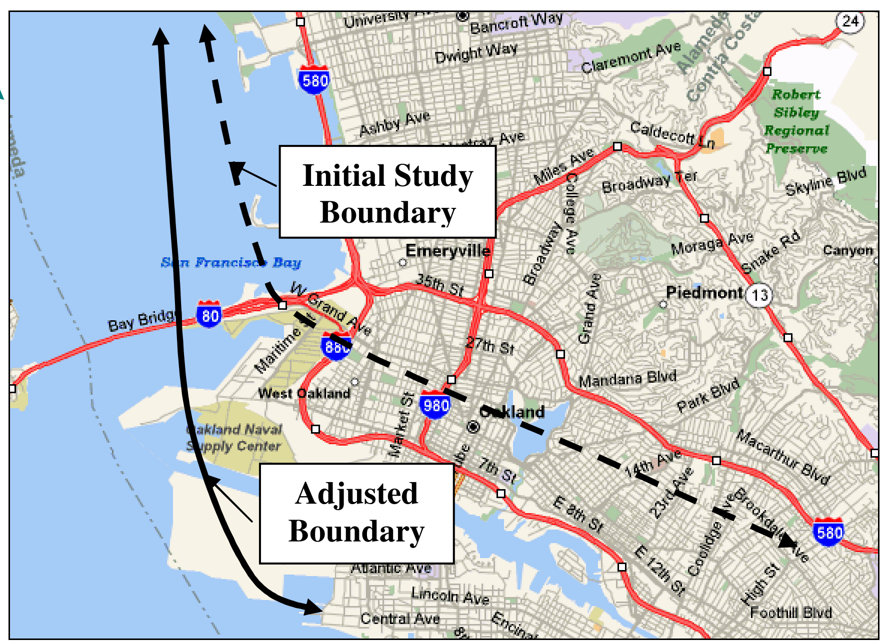
7.4.2 Origin-Destination Data

Travel-demand data are provided as origin-destination (O-D) matrices from periodic public surveys. The locations of travel origin and destinations in O-D data are aggregated by Traffic Analysis Zones (TAZs), which are about the size of a census tract in an urbanized area. O-D data contain three sets of data: (a) a "from" TAZ identification number; (b) a "to" TAZ identification number; and (c) the surveyed number of trips, or travel demand, between the two zones. These numbers referred to as an O-D matrix. The Import Wizard joins the O-D data geographically to the transportation network to create a subset demand for the network in the study area.



Base data source: Caltrans

Figure 7-1: Martinez-Testbed Study Region



Base data source: www.mapquest.com

Figure 7-2: Adjusted Boundary of Study Region within Oakland

Users import O-D data into REDARS™ 2 by providing a delimited text file with three columns. The TAZ "from" field is the first field, the TAZ "to" field is the second field, and the last field is the traffic demand. The Import Wizard dialog for the O-D data requires two additional parameters. The first parameter is the number of hours that the travel demand in the O-D matrices represents, and the second parameter is the factor for converting the system-wide travel time into a daily value. Although default values are provided, the user must inquire directly with the MPO or transportation agency providing the data to establish these factors.

Travel-demand data for the Martinez-Testbed study region (passenger and freight OD matrices) were received from the Bay Area Metropolitan Transportation Commission (MTC). The passenger-trip data (in PCU, or Passenger Car Units) contained four trip types for both 2-hour (7-8 AM), and 4-hour (6-9 AM) peak periods, resulting in eight O-D matrices. The freight data contained multiple O-D matrices by truck size (small, medium, and large) over 4-hour peak and off-peak periods. Because trip types by purpose are not analyzed by REDARS™ 2, the Bay Area O-D data were aggregated into two matrices, one for passenger traffic (summarized in Table 7-1a) and one for freight (summarized in Table 7-1b). The unit costs ($/hour) for travel time is used to convert the increase in system-wide travel time to economic loss. The unit-cost values that were used in this application were $13.75/hour for passenger trips and $72.65/hour for freight trips. These unit cost values were, based on data from the RAND California Statistics website (2003, http://ca.rand.org/stats/community/ trafficcongestion.html).

Table 7-1: Travel Demand

(a) Passenger Trips

PCU	Purpose 1	Purpose 2	Purpose 3	Purpose 4	Total
2-hour peak	1,666,829	183,720	55,067	4,456	1,910,072
4-hour peak	2,639,735	300,654	89,476	9,728	3,039,592

(b) Freight Trips

Trucks	Small	Medium	Large	Total
4-hour peak	63,414	5,813	12,956	82,183
Off-peak	133,396	13,221	28.785	175,402

In addition to the O-D matrix, the user supplies a TAZ boundary ESRI Shapefile in a geographic projection. The Import Wizard prompts the user to identify the field in the Shapefile that contains a unique identifier used to join the data to the OD matrix. The Bay Area TAZ file obtained from MTC consisted of 1,099 internal and 21 external zones over nine counties: Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma County. Figure 7-3 is a map created from the TAZ Shapefile.

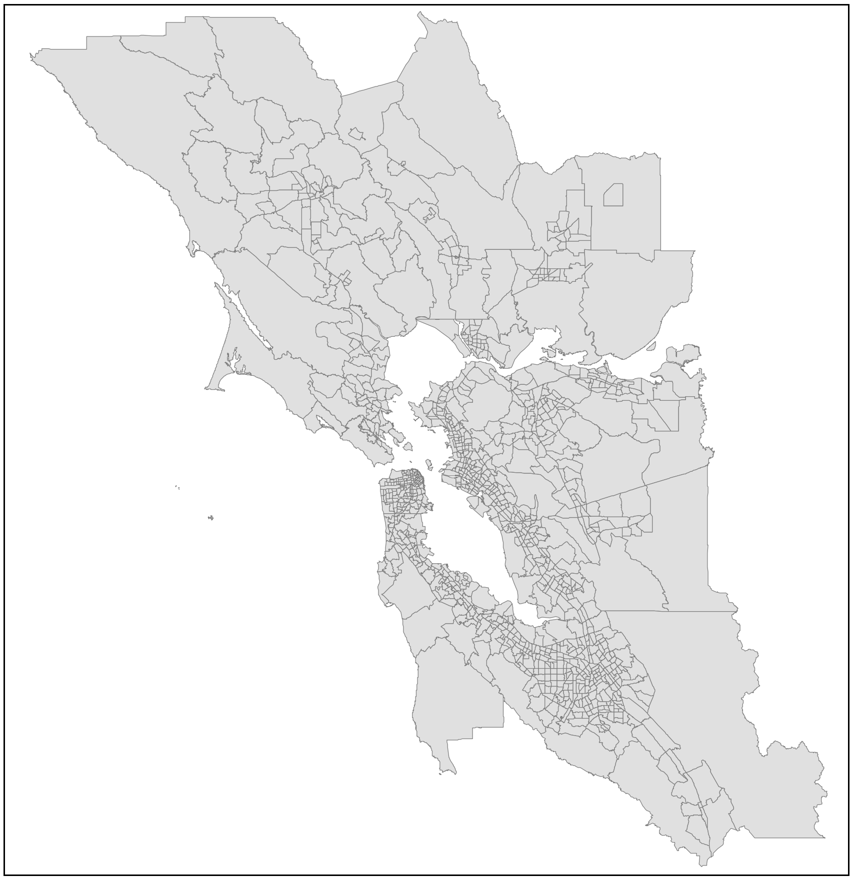


Figure 7-3: Bay Area MTC TAZs

7.4.3 Transportation Network Data

For transportation network data, the Import Wizard uses two nationally available databases distributed by FHWA: the National Highway Planning Network (NHPN) and the Highway Performance Monitoring System (HPMS). The NHPN is a transportation network that includes interstates, principal arterials, and rural minor arterials. These data are provided by the states and maintained by FHWA. It is a 1:100,000 scale network database that contains line features representing just over 450,000 miles of current and planned roads. HPMS provides the latest version of the NHPN in .e00 format at http://www.fhwa.dot.gov/planning/nhpn/ and documentation at http://www.fhwa.dot.gov/planning/nhpn/docs/index.html. The HPMS tracks public road mileage and is certified by state governors on an annual basis. Attributes that are collected include the extent, condition, performance, use, and operating characteristics of a given section of roadway. The database is not geographic, but contains a route number and a *from* and a *to* mile marker. This allows the Import Wizard to render the attributes of the HPMS on the NHPN through dynamic segmentation. Mapping the HPMS data using dynamic segmentation is subject to error if the data are not attributed correctly, as discussed further in Section 7.5. Both the HPMS and the NHPN data were downloaded from the FHWA website for the State of California. Figure 7-4 shows the NHPN map that was used in this demonstration project.

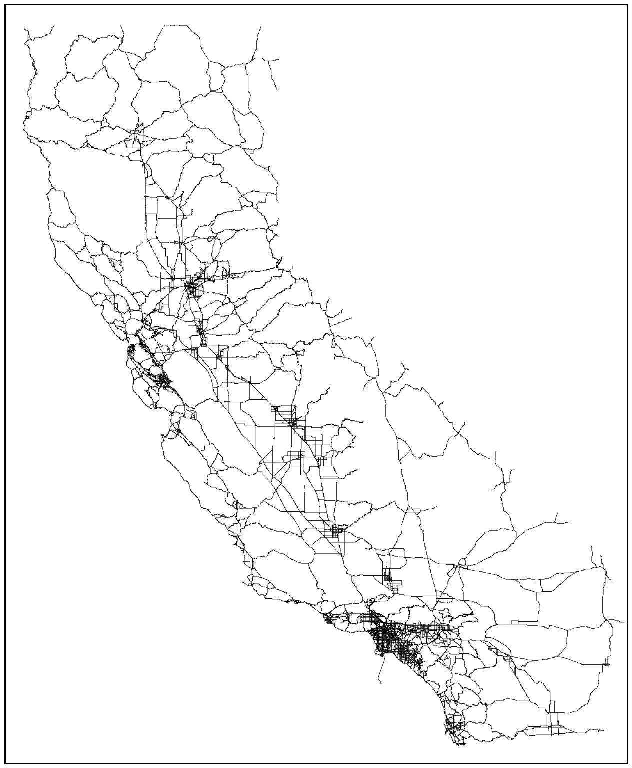


Figure 7-4: California NHPN Data

7.4.4 Highway Component Data (Bridges and Tunnels)

REDARS™ 2 uses the FHWA National Bridge Inventory (NBI) database to incorporate location, structural type, year built, and number of lanes of the components into the transportation network. As with the HPMS data, the route and milepost field within the NBI make it possible join the bridges and tunnels to the network through dynamic segmentation. The REDARS™ 2 data model incorporates both the geographical data and attributes from the NBI database. It is important to note that, although NBI maintains the locations of the bridges and tunnels in the latitude and longitude fields (ITEM 16 and 17), these fields are not used. The Import Wizard locates the bridges and tunnels using the LRS data, which allows a spatial join between the bridges and tunnels and the individual segments in the transportation network, thereby supporting REDARS™ 2 ability to assess disruption in network connectivity. Additionally, locating the bridges and tunnels through LRS can provide very accurate coordinates, if the milepost markers and route attributes in both databases are correct. At freeway intersections where the closest link may not correspond to the appropriate freeway, the latitude and longitude of the bridge location results in an incorrect spatial join. Additionally, FHWA does not plan to provide coordinates in future releases of the NBI due to security concerns. Because REDARS™ 2 cannot depend on the availability of coordinates and because the current Import Wizard does not utilize coordinates, increasing coordinate accuracy will not result in a more accurate representation of the bridge or tunnel location in REDARS™ 2 (see Section 7.5).

The NBI attributes, including the route and mile marker, were verified through comparison with the Caltrans database that is entitled *California Log of Bridges on State Highway* (www.dot.ca.gov/hq/structur/strmaint/brlog2.html). In addition, the bridge coordinates were available for selected bridges commonly found in Caltrans internal databases such as the SMART system and PONTIS. This data verified the location plotted through LRS.

7.4.5 NEHRP Soil Data

The REDARS™ 2 data model uses National Earthquake Hazard Reduction Program (NEHRP) soil classifications (e.g., Dobry et al., 2000) in order to provide soils data that can be used to estimate soil amplification effects on site-specific ground motions (see Chap. 4). To import these soil data into REDARS™ 2, the user provides an ESRI Shapefile in decimal degrees with the NEHRP soil class in a single column. The REDARS™ 2 Import Wizard will accept a default NEHRP soil type if soil is not available in GIS format. For California, these data are available from the California Geological Survey (CGS). Figure 7.5 provides a map of the NEHRP soil Shapefile obtained from CGS. Since the CGS soil map covers land surface only, the bridges located over water body are assigned a default NEHRP soil Type D (soft soil).

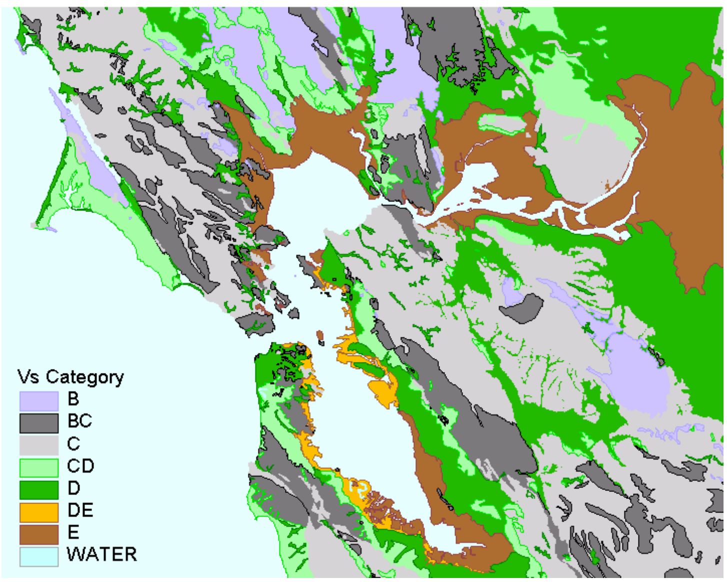


Figure 7-5: CGS NEHRP Soil Types Surrounding Study Region

Using the data described above, the Import Wizard created a REDARS™ 2 study region. The final region for the Martinez-Testbed highway system consisted of 194 TAZs (including 20 external TAZs), 2,102 uni-directional links (including 736 virtual links to connect TAZ nodes to actual network), 714 nodes, 352 bridges, and 9 tunnels (including the Caldecott tunnel). Figure 7-6 shows the final transportation network model for this system. Of course, as users ran the Import Wizard frequently throughout the beta-testing period, the study regions generated during these various runs often differed slightly from the study region discussed above. Consequently, the number of components from these runs may differ slightly from the above numbers.

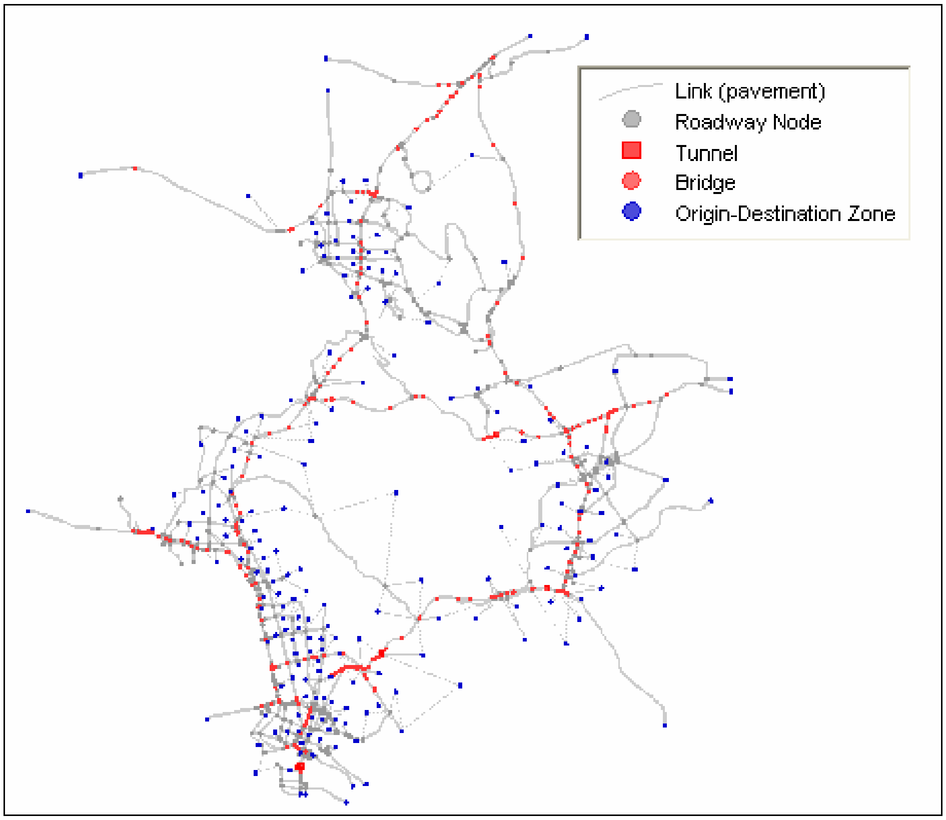


Figure 7-6: REDARS™ Study-Region Database

In addition to the default REDARS™ 2 database created by the Import Wizard, users can augment the REDARS™ 2 database to make the analysis more accurate. The project team incorporated the following data during the REDARS™ 2 demonstration study:

1. Caltrans provided liquefaction susceptibility data for eight bridges located near the cities of Berkeley and Oakland. The study region included six of the eight bridges, and the liquefaction data for these bridges were manually entered into the REDARS™ 2 database.
2. Caltrans provided information on the 2,239 bridges retrofitted before 2004 throughout the state. The study region included 121 bridges of these bridges, and the data for these bridges were added to the database.
3. The project team has created a 10,000-year earthquake walkthrough file for Coastal California (see Sec 4.2) The walkthrough file developed for SRA of the Martinez-Testbed system consisted of those earthquakes from the Coastal California file, that are located within about 200 miles of this Testbed study area.

7.5 BRIDGE DATA ASSESSMENTS FROM BETA-TESTING OF REDARS™ 2

Caltrans beta testing of REDARS™ 2 included an assessment of the the NBI bridge data that were accessed by the Import Wizard. Primary concerns included the accuracy and completeness of bridges as located by the Import Wizard, and the density of the road network represented by the NHPN. This section addresses these two concerns.

7.5.1 Accuracy and Completeness of NBI Bridge Locations

In the early stages of Import Wizard development, the REDARS™ team considered two approaches for specifying bridge location: real world coordinates (latitude and longitude), and LRS. Coordinates were available from the NBI database, and these coordinates were compared to the coordinates from the Caltrans SMART system for 11,224 bridges. The project team confirmed that these two data sets were identical. The NBI defines latitude (Item 16), longitude (Item 17) with 8 or 9 digits up to 1/100 of a second for the beginning of a bridge structure. If a bridge starts from a local street, as in the case with entrance ramps, the coordinate represents a location on the local street. Coordinates for exit ramps start on the freeway. As Figure 7-7 illustrates, coordinates for bridges do not always align with freeways and are frequently located near a freeway junction. In the best of cases, it is not easy to identify which freeway segment should be associated with a bridge. Bridges located at freeway intersections are even more problematic.

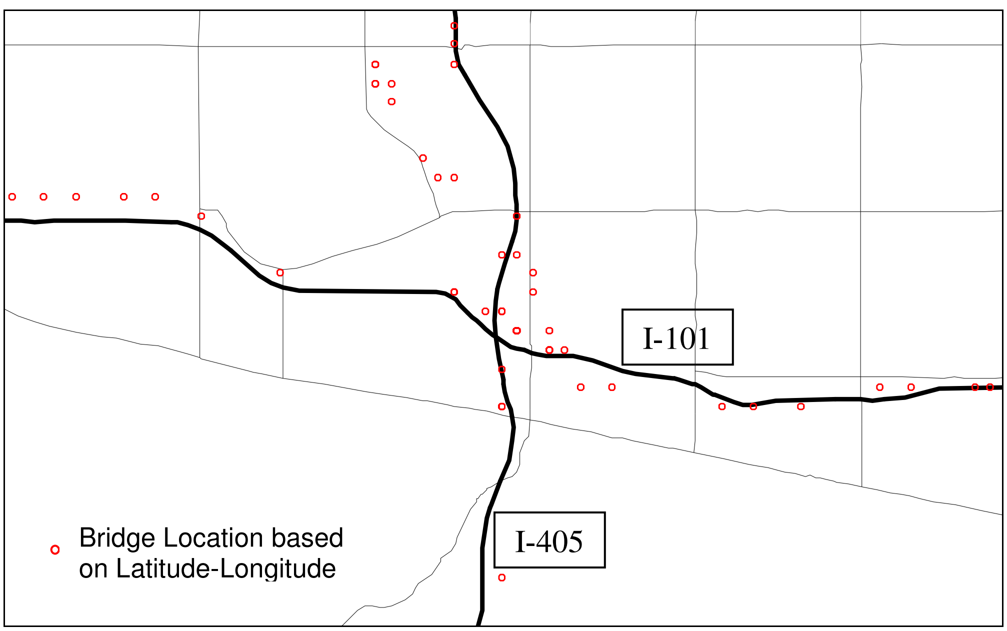


Figure 7-7: Bridge Location based on NBI Coordinates

As discussed in the beginning of this chapter, even if coordinates locate a bridge near a freeway, REDARS™ does not *assume* bridge locations for the nearest freeway segment. To assess connectivity, bridges are located through LRS as described in NCHRP (2001), and are implemented in the NHPN, HPMS, and NBI databases. The HPMS field manual provides a series of comprehensive instructions attributing the data (FHWA HPMS field manual, http://www.fhwa.dot.gov/ohim/hpmsmanl/hpms.htm). Figure 7-8 illustrates how LRS establishes location for a bridge with the unique identifier 53 105, route identifier 405, and milepost 215.6. Dynamic segmentation converts the linearly referenced bridge data into a location display on the base network between *From* milepost 215 and *To* milepost 216. Figure 7-9 shows bridge locations near the I-110 / I-105 junction that were identified by using this method with the NBI and NHPN LRS fields. This junction is especially complex due to the continuous car-pool ramps over the main lanes for non-car pool vehicles. Nevertheless, bridges align with freeway segments, allowing connectivity analysis.

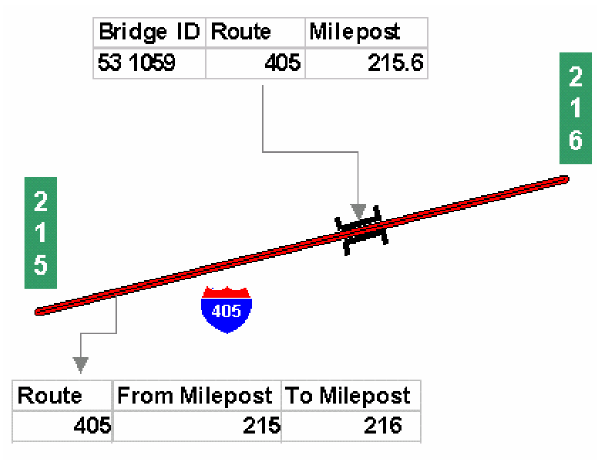


Figure 7-8: Locating a Bridge through Dynamic Segmentation

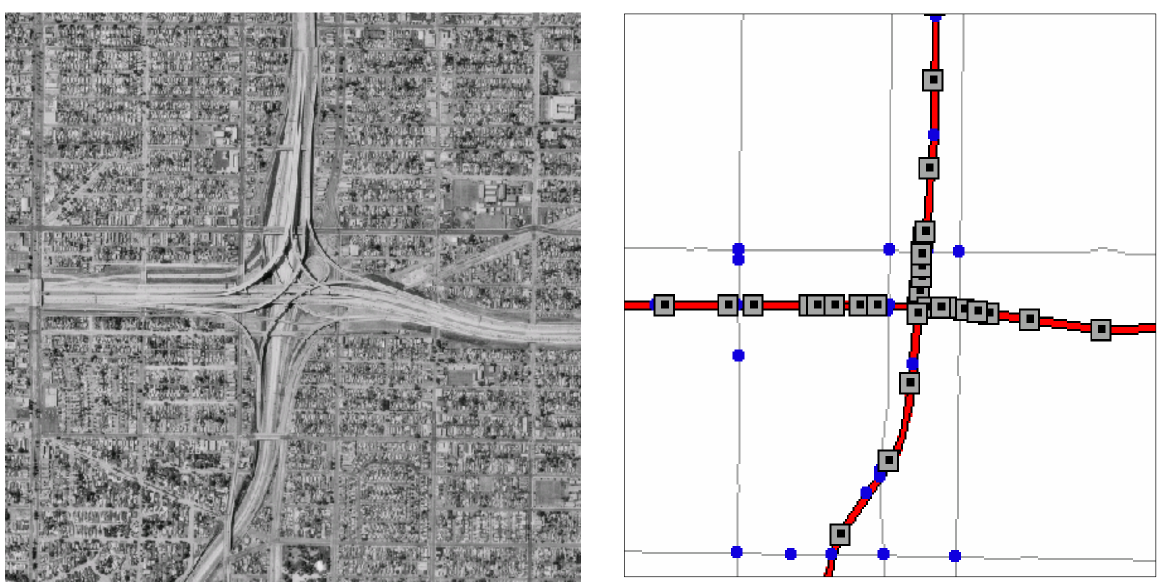


Figure 7-9: Bridge Locations based on NBI and NHPN LRS Fields

During beta testing, Caltrans' beta-testing staff observed that many bridges are not included in the database and that many facilities are incorrectly located. For example, only a few bridges are shown to be located on I-580 near Oakland, whereas that section of the freeway actually includes many bridges. In addition, the Caldecott Tunnel is shown to be located 18-km north of its actual location. Three factors are required for location through LRS: (a) Route ID; (b) Sub-Route ID; and (c) mile marker. If these three are not properly populated, or are not consistent between databases, the resulting locations will be incorrect. Section 7.5.2 details the problems that occur when these three fields do not agree.

7.5.2 Comparison of LRS-Based Bridge Locations with Real-World Coordinates

Figure 7-10 compares the NBI coordinate data with the NBI locations plotted on the NHPN through LRS. There are significant differences between the data sets. Approximately 1/3 of bridges did not have enough attribute information for LRS (3,497 red dots out of 12,224 bridges). In many cases, the sub-route ID did not match between NBI and NHPN, or the mile marker in the NBI did not match with a segment included in the NHPN. These bridges are not included in the final REDARS™ 2 database due to lack of information. For the 836 bridges shown in black dots (6.8% of the total bridges with latitude-longitude coordinates), the LRS location differs from the real world coordinates by more than 2 miles, which is likely to result in an incorrect association between the bridge location and the freeway link in REDARS™ 2. Figure 7-11 provides a detailed view of Figure 7-10 for the Bay Area. This figure shows that missing bridges systematically align with specific freeway routes. It is likely that the missing information is due to incompatible coding rules applied in the different databases, which negates a match.

To identify the reasons for this discrepancy, the project team carefully examined the NHPN and NBI databases for the Los Angeles highway-roadway system. Caltrans' Northridge Earthquake recovery report (Caltrans, 1995) documents the location of collapsed and severely damaged bridges. These data provided a third location which was used to cross check the NBI data. Figure 7-12 illustrates the three typical types of problems that were identified. These problems are described below.

Case 1: The NBI and NHPN record a different starting point for the mile marker. For example, only a few bridges were located on the SR-14 near I-5 intersection through LRS because either the NBI or the NHPN mile marker shifted 26 miles to northeast or southwest.

Case 2: The database contains a missing or incompatible sub-route or route ID. For example, there were no bridges was associated with SR-170 because the NBI database has no sub-route ID for these bridges, while SR-170 in NHPN has a sub-route ID. It is not clear whether SR-170 requires a sub-route ID, but in cases where these fields are either incompatible or use different naming conventions, bridges will not be located.

Case 3: A database contains flipped geographic segments. For example, some bridges on I-5, near Glendale have increasing mile markers as bridges proceed to the north, while in the NHPN, mile markers on I-5 increase toward south. In these cases, the beginning and ending nodes are essentially flipped, resulting in an incorrect location.

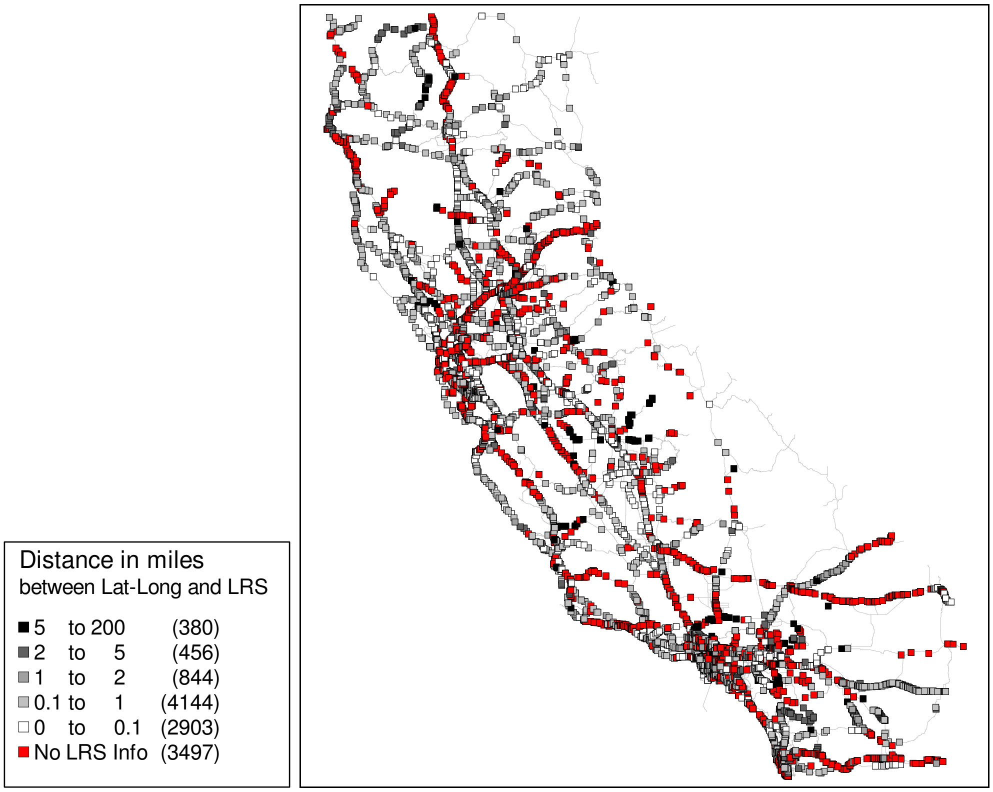


Figure 7-10: Discrepancies in NBI between LRS and Coordinate Locations for California

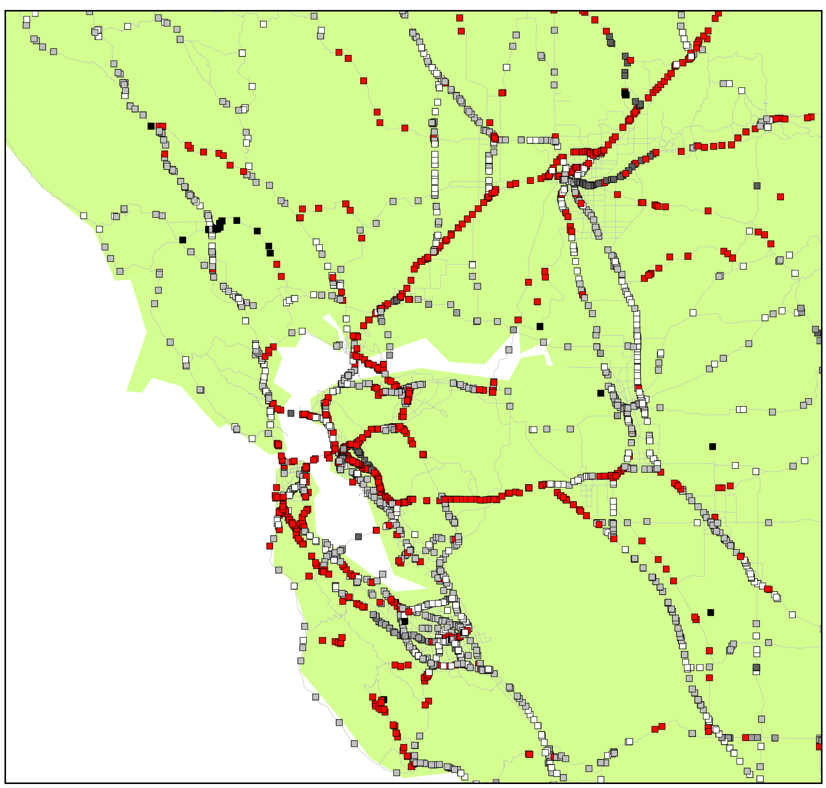


Figure 7-11: NBI Discrepancies between LRS and Coordinate Locations for Bay Area.

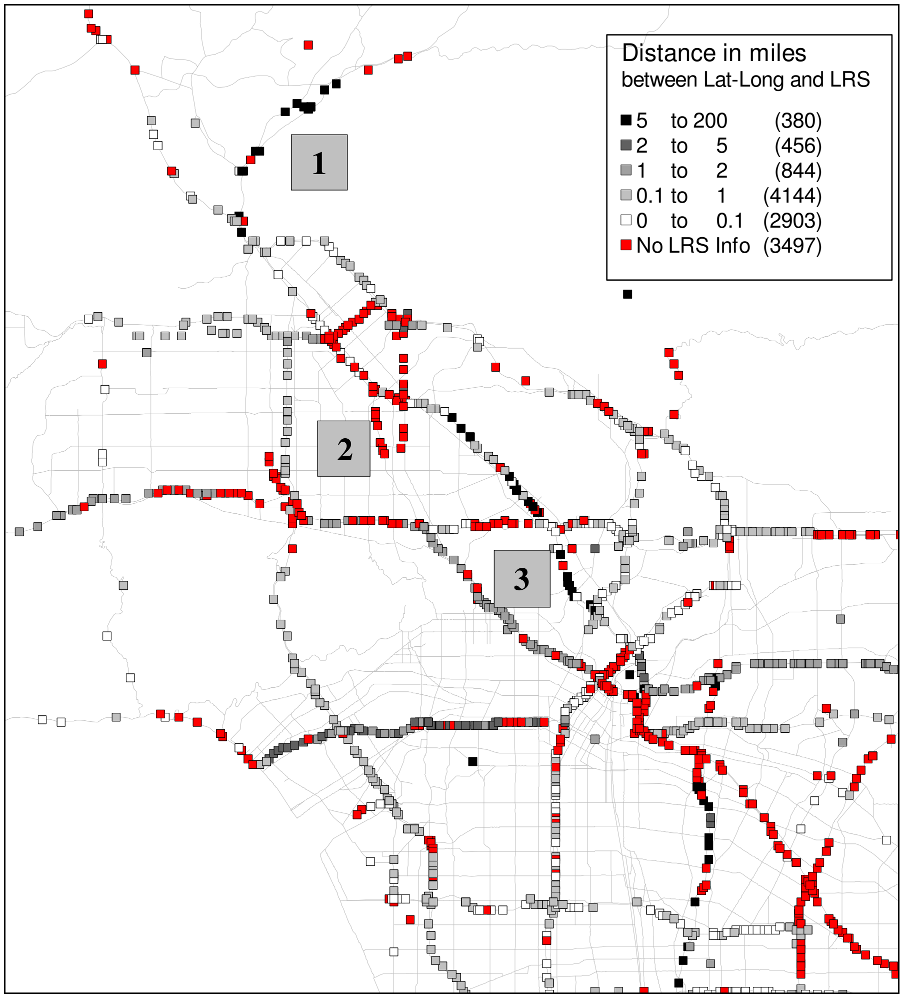
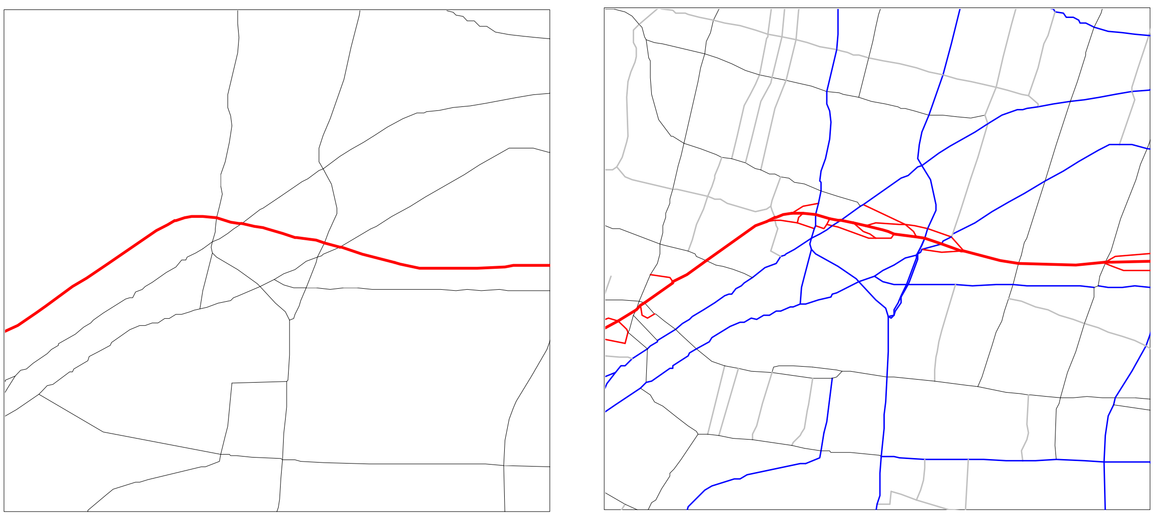


Figure 7-12: LRS Location vs. Latitude-Longitude Coordinate Mismatch in LA Area

7.5.3 Inadequacy of Sparse Transportation Network represented by NHPN

During the beta-testing process, the Caltrans team noted that the sparse transportation network did not contain many essential arterials. A more detailed street network in REDARS™ 2 would result in a more realistic system analysis. Caltrans has established a detailed series of network topology maps statewide, which are named XX_func where XX is the abbreviation of each county name. Whereas NHPN contains only select local streets such as major arterials, the Caltrans network contains detailed local streets (Fig. 7-13). This discussion considers the benefits and costs of replacing NHPN with the Caltrans network.

There are several benefits to integrating the Caltrans network into REDARS™ 2. The representation of ramps in the Caltrans network will prevent overestimation of economic loss resulting from locating ramps on freeway lanes. As Figure 7-13a illustrates, NHPN does not include links that represent ramps. Consequently, all bridges are associated with the freeway. This means that the predicted damage state for bridges on freeway ramps will be incorrectly associated directly with the freeway itself, and will incorrectly indicate an interruption of traffic flow along that freeway. However, use of Caltrans' network data could make it possible to circumvent this problem, by enabling the bridges to be linked to actual ramps rather than the freeway. Also, detailed network data can be used to analyze realistic detour routes near collapsed bridge sites. Figure 7-14 illustrates the I-10 detour in Los Angeles that was established immediately after the 1994 Northridge Earthquake and is shown on the LA_func map. Currently, REDARS™ 2 assigns a default residual capacity to model detours that is not representative of any given specific location. If detailed network data are integrated into REDARS™ 2, detour routes can be analyzed. Additionally, including a more detailed network results in an estimated network capacity that is closer to actual capacity that, in turn, would result in a more accurate baseline calibration for the Variable Demand Model (VDM).



(a) from NHPN Database **(b) from Caltrans Network Database**

Figure 7-13: Comparison of NHPN and Caltrans Network

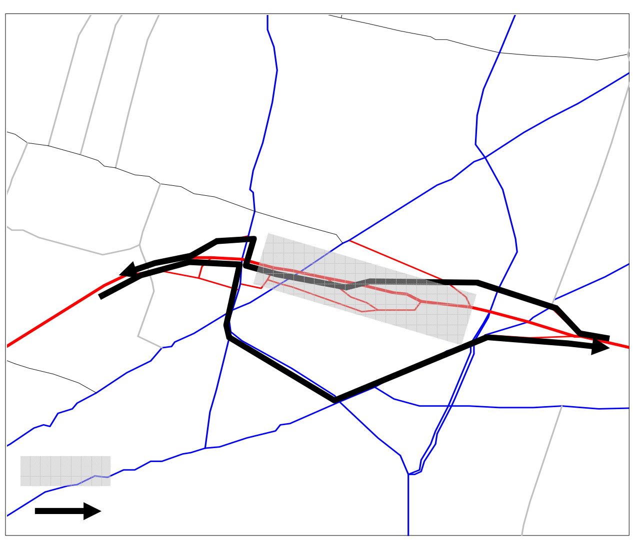


Figure 6-14: Detour Established after 1994 Northridge Earthquake on Caltrans Network

There are several complications to integrating detailed network data into REDARS™ 2. The transportation network-analysis procedure in REDARS™ 2 requires the vast majority of the overall SRA running time and, as more links are added, processing time would increase exponentially. In addition, the Import Wizard is designed to work on a national level and does not consider local datasets. The effort that would be required to modify the Caltrans network into a format useable by the Import Wizard is unknown. Yet another complication is the location of bridges through dynamic segmentation. The Caltrans network does not currently support the location of NBI bridges through LRS and does not include mile marker, although additional Caltrans datasets may be available to facilitate this process. The final impact of a more detailed network on SRA is unknown, and the affects may be minimal when compared to the physical time required to modify the base data or the program and the increase in running time for probabilistic analysis. Additional research is needed to explore both the benefits and the costs of integrating a more detailed network.

7.6 RECOMMENDATIONS

This chapter has reviewed the data compiled to create the default REDARS™ 2 database for the Martinez-Testbed roadway system. During the beta-testing period, the project team members discovered that many bridge structures were not included in REDARS™ 2 databases due to inconsistencies between the NBI and NHPN. A similar problem was noted with missing roadways in the NHPN. In both cases, a more detailed geographic representation was available through Caltrans, but the attribute data from Caltrans was not in a format that could be used directly by the Import Wizard without significant data massaging.

A master California network data package would address these issues. The development of a series of geographic, and database queries could merge the desired attributes from the federal and state level databases into a single REDARS™ 2 compatible data set. Caltrans currently has several bridge databases such as NBI, California Bridge Log (online), and SMART that could be examined to resolve data discrepancies such as mile marker, route or sub-route name, or other attributes of component location. Caltrans network data, such as the detailed roadway maps created by the Office of Traffic Operation, could be collected and integrated into a statewide California state REDARS™ 2 data package. Designated users would be able to incorporate local TAZ data and create REDARS™ 2 databases that reflect the best available Caltrans data. This, in turn, would enable Caltrans to maintain a single centralized database that various divisions or user groups statewide could access, in order to obtain the most current and accurate data to run REDARS™ 2. In addition, this would minimize the potential for different groups within Caltrans to use incompatible or outdated datasets, and would allow the database to be managed by one group within Caltrans.

CHAPTER 8
TASK 6: SEISMIC RISK ANALYSIS OF TESTBED HIGHWAY-ROADWAY NETWORK

8.1 OBJECTIVE

Under Task 6, the RDT guided Caltrans' project staff during their applications of REDARS™ 2 to the Martinez-Testbed roadway system shown in Figure 8-1. These applications had two purposes. First, they enabled Caltrans' staff to become familiar with the REDARS™ 2 software, and how it can be used for SRA of highway-roadway systems throughout California. In addition, these applications enabled Caltrans to beta test the software, during which they provided the RDT with valuable feedback and suggestions for addressing any bugs that were encountered and for improving the usability and technical features of the software.

8.2 MARTINEZ-TESTBED ROADWAY SYSTEM

The Martinez-Testbed roadway system extends through the northern and eastern sections of the Eastern San Francisco Bay Area. It was selected to be a testbed roadway system for this project because:

- It has a simple yet redundant configuration with opportunities for future expansion;
- It contains important roadway transportation links, including the I-80 and I-680 freeways which are major routes into the Bay Area from the east. In addition, the I-680 freeway is considered by Caltrans to be a "lifeline route", which must be able to accommodate emergency traffic after an earthquake;
- It has a very high potential for significant seismic hazards. For example, it is bisected by the Hayward and Green-Valley Fault systems, and is also near other fault systems that could generate significant ground shaking. In addition, the segment of the system that is adjacent to the San Francisco Bay between Emeryville and Richmond is sited on soils with a high potential for earthquake-induced liquefaction.
- It includes major bridges that cross over water (the Benicia-Martinez and Carquinez Bridges) as well as a major tunnel (the Caldecott Tunnel), for which the development of user-specified fragility models may be appropriate[1].
- It covers two State-Plane GIS coordinate systems, which require additional data infusion and integration that is typical of applications that may arise in other parts of California.

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[1] The original plans for this project called for Caltrans to develop user-specified fragility models for these major structures. However, as noted in Chapter 5, this could not be carried out because of time constraints of key personnel in Caltrans who were to be assigned to carry out this task.

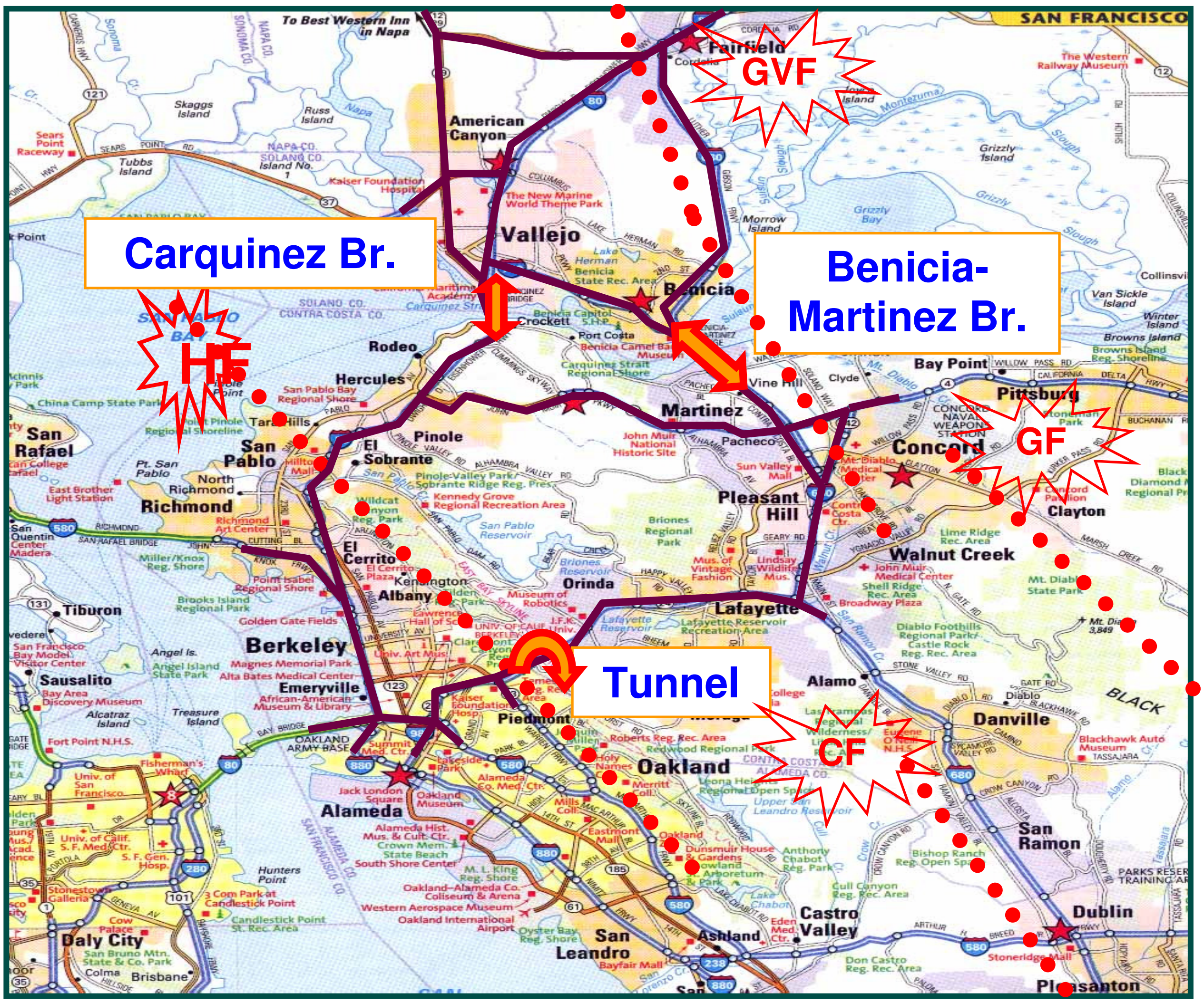

Figure 8-1. Martinez-Testbed Roadway System

8.3 SRA APPLICATION SUMMARY

At the onset of this task, the RDT provided Caltrans' project staff with a detailed list of possible calculations and beta-testing checks that they could carry out under this task, and also reviewed this list with Caltrans staff (see Tables 8-1 through 8-4). In this, it was recognized that this list is extensive, and the actual calculations and checks that could be carried out (in addition to identification of possible bugs in the software) would depend on the staff's available time for these efforts, in the midst of their other responsibilities. However, it was felt that this list could represent a guideline for Caltrans staff to follow in the course of these calculation and beta testing efforts, so they might use their available time in as efficient a manner as possible.

These suggested tasks covered four aspects of the application and testing of REDARS™ 2: (a) development of input data; (b) deterministic analysis applications; (c) probabilistic analysis application; and (d) development of results to guide seismic-risk reduction decision making. Section 8.4 summarizes the results of Caltran's activities to address each of these aspects.

Table 8-1
Checklist of REDARS™ 2 Features Available for Possible Testing: Input Data

Input Data	Feature for Possible Checking	Description
Initial Data Development by User	User compilation of initial data prior to running REDARS™ 2 Import Wizard and core program	Identify study area Obtain data from Metropolitan Planning Organization Establish unit economic loss coefficients Identify post-earthquake times for estimation of losses
Import Wizard	Access of publicly available databases	Roadway topology and attributes Bridge locations and attributes Trip types (auto, freight types 1, 2… N) Origin-destination (O-D) zones Pre-EQ trip tables for each trip type Regional NEHRP soils map
	Input-data development steps	User implementation steps Import Wizard (IW) check for database inconsistencies IW check of network model and O-D zone connectivity and /continuity User specification of unit economic losses, IW graphical display of study area IW graphical display of regional NEHRP soil map NEHRP soil classifications at each component site
Shake-Map	Ground-motion maps from Shake-Map earthquake event	User downloading of Shake-Map ground-motion data into REDARS™ 2
Other Input Data	Liquefaction hazards input data	User designation of potentially liquefiable sites within roadway system User development of site-specific input data for estimating liquefaction hazards
	Walkthrough table	User selection of walkthrough table that shows earthquake occurrences over time, and fault attributes for each fault-based earthquake
	Default input data	Completeness, accuracy, and consistency checks User override of any default input data

Table 8-2
Checklist of REDARS™ 2 Features Available for Possible Testing: Deterministic Analysis

Feature for Possible Checking	Description
Earthquake Events	Select any event from walkthrough table User-designation of arbitrary earthquake event Shake-Map earthquake event
Ground Motions	Computed by ground-motion model built into REDARS 2 Obtained from ShakeMap data
Other Seismic Hazards (does not apply if Shake-Map ground motions used)	Liquefaction hazards can be included Surface-fault-rupture hazards can be included (only if fault-based earthquake from walkthrough table is being considered)
Default Component Modeling (Damage State and Repair Models)	Bridges with or without column-jacket retrofit Bridges that cross over other roadways Approach fills Pavements Tunnels (user-specified fragility curves and repair models) User-override of any default model
Network Analysis	Variable-demand model including effects of trips foregone Can include separate trip tables for each trip type
Output Options	Tabulations of economic losses due to repair costs, travel time delays, and trips foregone Tabulated data or GIS maps for: Ground motions throughout roadway system Permanent ground displacements throughout system (if Shake-Map option not used) Component damage states throughout system At any post-earthquake time, can obtain tabulated data or GIS Displays for: System states (traffic states throughout roadway system) Access times or egress times to/from any user-designated location in study area Trip attraction or production to/from each user-designated location Travel times along any user-designated route

Table 8-3
Checklist of REDARS 2 Features Available for Possible Testing: Probabilistic Analysis

Feature for Possible Checking	Description
Earthquake Events	Total probabilistic: From multi-year walkthrough table Conditional probabilistic: Modify walkthrough table to have same earthquake occurring during each year of walkthrough
Ground Motions	Computed by any ground-motion model (with uncertainties) built into REDARS 2 ground-motion model library
Other Seismic Hazards	Liquefaction Hazards (with uncertainties) can be Included Surface fault rupture hazards (with uncertainties) can be included
Default Component Modeling (Damage State and Repair Models)	Same as list for deterministic analysis given in Table 8-2 User can override of any default model
Network Analysis	Same as summarized for deterministic analysis in Table 8-2
Probabilistic Output Options from Overall Analysis for Multiple Scenarios in Walkthrough Table	Continuous displays of confidence intervals (CIs) for expected economic losses as walkthrough analysis proceeds Users can terminate probabilistic SRA when they determine that CI values are acceptable Graphical or tabulated probabilities of exceedance at default or user-specified exposure times for: Economic losses due to repair costs, travel time delays, and trips foregone At any post-earthquake time: Access or egress times to/from any user-specified O-D zone Trip attraction/production at any user-specified O-D zone Travel-time delays for any user-specified route Ground motions at any user-specified component site Probability of occurrence of various damage states for any user-specified bridge or tunnel Users can interrupt SRA at any time during walkthrough analysis, to examine intermediate results obtained thus far. Any of above probabilistic results can be displayed at this time. User can then restart and continue SRA.
Output Options from Individual Scenario Earthquakes in Walkthrough Table	Same as list for deterministic analysis at bottom of Table 6-2.

Table 8-4.
Checklist of Possible Applications of REDARS™ 2 to Guide Seismic Improvement Decision Making

Improvement	Decision	Use of REDARS™ 2 to Guide Decision
Bridges	Which bridges should be retrofitted first? Which bridges should be repaired and opened to traffic first after an actual earthquake? What is the effect of alternative levels of retrofit on the potential losses due to traffic flow disruption?	Modify bridge model's structural capacities to simulate retrofit or post-earthquake repair Can modify bridge damage state results obtained from deterministic analysis, to simulate retrofit or post-earthquake repair. Adjust input soil parameters at liquefiable sites to represent effects of soil improvement.
Lifeline Routes	Are Caltrans-designated lifeline routes able to maintain acceptable continuity of emergency traffic after an earthquake? If not, what seismic improvements can be made along these routes? Might alternative lifeline routes be considered?	Evaluate travel times along user-specified routes. Evaluate effects of adding lanes (removal of parking lanes, construction of adjacent roadway along damaged route where space is available). Evaluate effects of improving structural capacities of bridges or other components along these routes.
Repair Strategies	Should a bonus incentive process be used to repair bridge damage along a major freeways/roadway? Are current repair resources (materials, equipment, and labor) adequate to carry out roadway system repairs sufficiently fast so as to limit losses due to roadway system damage to acceptable levels?	Modify default repair models to reflect more rapid repairs and larger implementation costs. Run sensitivity studies to assess effects of rate of repair on potential losses. Include effects of increased costs that would be required to rapidly mobilize increased repair resources that might more effectively limit these losses.
System	What are the benefits of constructing new roadways adjacent to existing roadways to provide alternative routes along non-redundant sections of the roadway system? What should be the traffic capacities of these additional roadways?	Modify current network model to include adjacent detour links. Run sensitivity studies to assess how losses due to traffic disruption are affected by number of lanes along these additional routes.

8.4 CALTRANS' APPLICATIONS OF REDARS™ 2

Caltrans' applications and beta testing of REDARS™ 2 extended over a time period of five months and through the end of December 2005 (which was the targeted cutoff date for completion of the beta testing under this project). During this period, they successfully completed virtually all of the applications pertaining to input data development (Table 8-1) and deterministic analysis (Table 8-2). In addition, work was initiated on the implementation of probabilistic analysis calculations (Table 8-3) and on development of REDARS™ 2 results to guide seismic-risk-reduction decision making (Task 8-4). During these applications, Caltrans' staff gained extensive experience in the development of input data for REDARS™ 2 and in its application.

Under their FHWA-MCEER project, the RDT carried out a detailed demonstration application of REDARS™ 2 to the roadway system that extends through the northern, western, and central portions of the greater Los Angeles (LA), California area. These results are documented in the final technical manual for that project (Werner et al., 2006). They include examples of probabilistic applications of REDARS™ 2 , as well as the development of results to guide decision making.

The chapter of the FHWA-MCEER report that describes this demonstration application is reproduced in this report as Appendix D. In addition, the RDT can provide Caltrans will all of our data files for this application. It is recommended that Caltrans' staff apply REDARS™ 2 to this same LA highway-roadway system, in order to gain further practice and experience in carrying out probabilistic results and in developing results to guide decision making. The RDT could work with Caltrans to guide their efforts in these additional applications.

8.5 CALTRANS' RECOMMENDATIONS REGARDING REDARS™ 2 SOFTWARE

In addition to identifying several bugs in the REDARS™ 2 beta software (which were corrected by the RDT), Caltrans' beta testing of this software resulted in several helpful suggestions for improving the aspects of the software related to the engineering and SRA calculations and output, the software's graphical user interface (GUI), the Import Wizard, and the organization of the REDARS™ 2 software. The RDT has addressed and incorporated as many of these recommended upgrades as possible within the project's time and budget constraints. Those recommendations that could not be incorporated at this time have been tabulated and prioritized for inclusion into the software under a follow-on project. Caltrans' interactions with the RDT during their beta testing of REDARS™ 2 provided numerous suggestions and recommendations.

CHAPTER 9
CONCLUDING COMMENTS

9.1 CURRENT STATE OF DEVELOPMENT

The REDARS™ 2 SRA methodology and software have been under development for the past several years. With significant support from Caltrans, as well as from FHWA and MCEER, the software has developed to the point where it is now a user-friendly software package for applying what is now a state-of-the art methodology for SRA of highway-roadway systems. As such, it can provide significant support to Caltrans' future seismic-risk-reduction programs. In this regard, it can serve both as a pre-earthquake planning tool for assessing how various seismic-risk-reduction options could reduce losses due to earthquake-induced disruption of system-wide traffic flows, and well as a post-earthquake emergency-response tool in real time after an actual earthquake that would support Caltrans' assessments of alternative strategies for mitigating traffic congestion and restoring the functionality of the highway-roadway system.

REDARS™ 2 is now ready for further application to real-world applications that will arise within Caltrans as they strive to continue to develop their seismic-risk-reduction planning capabilities. This could not only support Caltrans in their risk-reduction activities, but would also enable Caltrans to provide further feedback/suggestions to the REDARS™ Development Team that would enable them continue to further develop this SRA methodology and software so as to further improve REDARS™ capabilities for effectively meeting Caltrans' seismic-risk-reduction needs.

9.2 DECISION-GUIDANCE TOOL

When considering various seismic-risk-reduction decision options, Caltrans must weigh several factors. These not only including engineering factors, such as the effectiveness of the different options in reducing life-safety risks, but also other non-quantifiable factors such as the financial, legal, political, administrative, social issues and constraints that will inevitably arise during the decision-making process.

There is one additional factor that has often not been directly considered in Caltrans' seismic-risk-reduction decision making -- the effectiveness of these alternative decisions in reducing losses due to earthquake-induced disruption of the highway-roadway system. Past experience has shown that such disruptions can lead to extensive economic losses to the impacted region and can also affect the region's emergency response and recovery processes (Caltrans, 1995).

One reason for the past limited consideration of these disruptions has been the lack of a technically sound and user-friendly process for assessing seismic risks to the highway-roadway system. This gap is now being filled by the development of the REDARS™ 2 SRA methodology that has been described in this report. This methodology, which includes many Caltrans-specific default damage-state and repair models for bridges, approach fills, pavements, and tunnels, can assess the effectiveness of various seismic-risk-reduction options in reducing potential losses due to earthquake-induced roadway system and traffic disruptions. This is illustrated by the example applications of REDARS™ 2 that are provided in Appendix D of this report.

In view of the importance of these losses during past earthquakes, the effectiveness of the seismic-risk-reduction options in reducing these losses should be considered along with the other decision factors listed above. This would provide Caltrans with an expanded basis for making a more informed decision that would serve the needs of the affected region.

9.3 FUTURE DIRECTIONS

Caltrans' beta-testing of REDARS™ 2 under this project has identified the need for various improvements of the current software and input data. These recommended improvements are discussed in Chapter 8 of this report. Table 9-1 lists additional recommendations for further improvement of the various REDARS™ 2 models. These recommendations are further discussed in Werner et al. (2006).

The developers of REDARS™ 2 have foreseen that, as for any major software package, the continued development of the software and the SRA methodology and models will be an ongoing living process that will continue as long as REDARS™ exists. To facilitate the incorporation of future model improvements, the REDARS™ software has been developed as a modular package, in which the various modules contain the hazards, component, and transportation-network analysis models and procedures that comprise this software and methodology. When future model and analysis procedure improvements are identified and selected for inclusion in future versions of REDARS™, they will require programming modifications only for the individual modules in which the improvements will reside, and will not require modification of rest of the REDARS™ software.

One other anticipated notable future direction of REDARS™ is its possible extension to address additional natural hazards as well as various man-made hazards. The structure of the basic REDARS™ platform facilitates this extension. This would enable future versions of REDARS™ to be applied to other natural hazards that are of importance to Caltrans, such as flooding, as well as man-made hazards.

Other future improvements and directions for the REDARS™ methodology and software will inevitably be identified as REDARS™ continues to be used actual real-world applications by Caltrans. As noted in Section 9.1, the recommendations received as a result of these applications will be a valuable resource for the continued development and usefulness of REDARS™ as a key Caltrans risk-reduction, emergency-response, and decision-guidance tool.

Table 9-1.
Future Directions - Model Improvements

Model	Recommended Improvement
Bridge Fragility Models: Ground Shaking Hazards	Work under this Caltrans project, the FEMA-MCEER project (Werner et al., 2006) and discussions during past Tri-Center workshops (TCW, 2003 and 2005), have all demonstrated the significant need to develop improved REDARS™ default models for estimating bridge damage due to ground-shaking hazards. This work should also address the availability within Caltrans of the bridge-attribute data that would be needed as input to the improved models that are developed,
Bridge Fragility Models: Permanent-Ground-Displacement Hazards	The currently-available models for estimating bridge damage due to permanent-ground-displacement hazards (due to liquefaction, landslide, and surface fault rupture) are even less developed than the above models for estimating bridge damage due to ground shaking. . Work toward developing such models that are suitable for use as default models in future versions of REDARS™ is encouraged. The availability within Caltrans of electronic databases of the soils and structural data needed to implement these models should also be addressed as part of this task.
Seismic-Hazard Models	The ground-motion models that were developed under the recent Next-Generation-Attenuation (NGA) project (Abrahamson, et al., 2006) should be included in the REDARS™ 2 Seismic-Hazard Module. This module should also be extended to include: (a) a landslide-hazards model; and (b) upgrade of the current fault-rupture-hazard model to consider multiple fault-rupture segments instead of only a single segment.
Network Analysis	The REDARS™ 2 network-analysis procedure should be extended to 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-roadway system; (b) development of improved trip-demand calibration tools for use in baseline (pre-earthquake) analyses of system-wide traffic flows and travel times; and (c) incorporation of results from external region-wide assessments of earthquake effects on the trips entering from or leaving from the study area to be analyzed..
Integration with Caltrans ShakeCast Program	Caltrans is currently involved in the development of a ShakeCast program to estimate bridge damage from ShakeMap estimates of ground motions. The possible integration of REDARS with the ShakeCast work should be assessed.