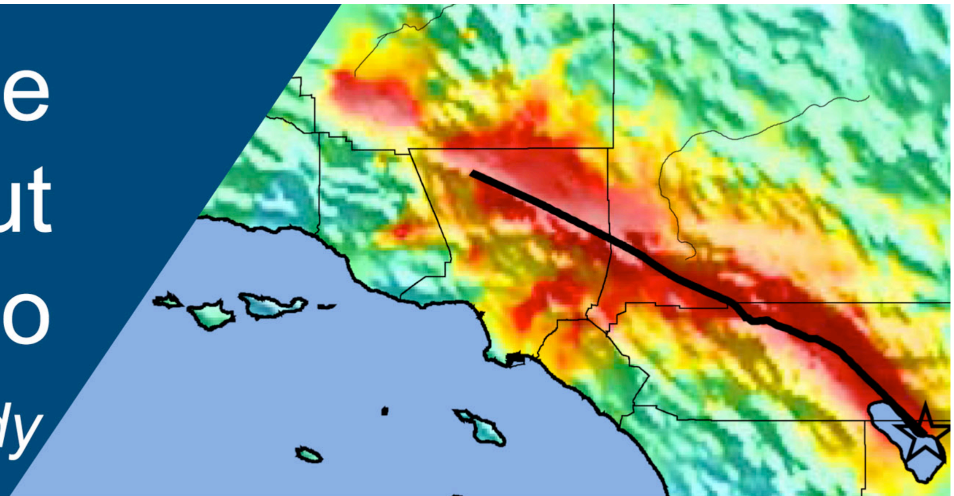
The ShakeOut Scenario

Supplemental Study



Analysis of Risks to Southern California Highway System

Prepared for

United States Geological Survey

Pasadena CA

and

California Geological Survey

Sacramento CA

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Note: over the course of the ShakeOut Scenario, the project name evolved. Where a study mentions *the SoSAFE Scenario* or *San Andreas Fault Scenario,* it refers to what is now named the ShakeOut Scenario.

Final Report

ANALYSIS OF RISKS TO SOUTHERN CALIFORNIA HIGHWAY SYSTEM DUE TO M7.8 EARTHQUAKE ALONG SOUTHERN SAN ANDREAS FAULT

by

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

As part of its Multi-Hazards Demonstration Project, the United States Geological Survey (USGS) is undertaking a multidisciplinary “Golden Guardian” (GG) exercise for assessing the resiliency of Southern California (SC) following a Magnitude 7.8 earthquake along a segment of the southern San Andreas Fault that extends from Bombay Beach along the Salton Sea to Lake Hughes in the Traverse Range north of Los Angeles.

Vital to the resiliency of the overall SC region will be the post-earthquake resiliency of the region’s highway system. One important aspect of this resiliency will be the seismic performance of the system’s bridges and other components, which has been the focus of highway-system earthquake engineering activities not only in California but also in other earthquake-prone regions of the United States and the world. These engineering activities have most typically focused on the development of bridge seismic design and retrofit procedures that will enable the bridges to avoid collapse and protect life safety in the event of a major earthquake. The California Department of Transportation (Caltrans) has been a world leader in the development and implementation of innovative design and retrofit methods that are directed toward insuring that this seismic performance requirement will be met for its bridges statewide.

However, the seismic performance of the state’s bridges, in terms of their ability to avoid collapse and protect life safety, is only one of several factors that will affect the resiliency of the state’s highway system. Other factors that will have a key effect on the system’s resiliency are: (a) the extent to which any earthquake damage to the state’s bridges will be repairable within an acceptable time after the earthquake; and (b) the characteristics of the highway-roadway system itself. System characteristics that will affect its post-earthquake resiliency include the system’s network configuration, the redundancies and traffic-carrying capacities of the various freeways and roadways that comprise the system, the locations of the bridges and other components along these roadways, and trip demands (including trip volumes, types, and origins and destinations) that the highway-roadway system must accommodate.

It is also important to recognize the variety of measures that can be used to improve the post-earthquake resiliency of the region’s highway system. These include: (a) engineering methods, such as the continued development of improved seismic design and retrofit methods; (b) post-earthquake repair planning, including plans to ensure that adequate repair resources can be rapidly mobilized after a major earthquake and deployed to sites of damaged components; and (c) emergency traffic-management planning, including plans for redirecting traffic and adjusting traffic flows so as to reduce traffic delays while repairs of the earthquake damage are proceeding.

1.2 PROJECT OBJECTIVE

The objective of this project has been to perform a single deterministic analysis of the seismic risks to the SC highway system due to the Magnitude 7.8 scenario earthquake that is being considered under this GG exercise. This analysis has been conducted using a new methodology and software package that is named REDARS™ 2 (**<u>R</u>**isks from **<u>E</u>**arthquake **<u>DA</u>**mage to **<u>R</u>**oadway **<u>S</u>**ystems). REDARS™ 2 estimates of post-earthquake traffic flows, travel times, and trip demands, and potential losses that result from earthquake-induced traffic and travel disruptions throughout the system as well as repair costs. The analyses consider: (a) the seismic hazards throughout the highway system, (b) the damageability of the system's bridges and other components when they are subjected to these hazards: (c) rates of repair of this damage, (d) how closures of damaged links while the repairs are proceeding will affect system-wide travel times and trip demands and the post-earthquake resilience of the highway system; and (e) economic losses due to repair costs, increased travel times and reduced trip demands. The REDARS™ 2 methodology is further described in Chapter 2 of this report.

1.3 PROJECT SCOPE

The scope of this project has been organized into the following three tasks:

- ***Task 1: Input Data.*** Under Task 1, the input data needed to implement the REDARS™ 2 analysis has been developed. This includes: (a) development of origin-destination (O-D) trip-table data for the eight SC counties; (b) preparation of highway-roadway network data that define the locations, traffic capacities, and redundancies of the roadways throughout the system; and (c) locations of bridges along these roadways. Chapter 3 of this report describes the development of these data under this project.
- ***Task 2. Seismic Hazard Results Review.*** The REDARS™ 2 analysis of the seismic risks to the SC highway system are based on shape files and tabulated data provided by USGS that define spatial distributions and intensities of system-wide ground shaking and ground displacement hazards due to the Magnitude .7.8 scenario earthquake. Under Task 2, these files have been reviewed in collaboration with USGS staff to assure that they could be readily input into the REDARS™ 2 software. It is noted that the seismic hazards considered in the REDARS™ 2 analyses included region-wide ground motions, surface fault rupture along the Southern San Andreas Fault, landslide hazards with the Cajon Pass and along I-10 at the San Gorgonio Pass, and liquefaction in the San Gorgonio Pass, and Coachella Valley areas. At the time of our analysis, no data were available regarding landslide and liquefaction hazards at other locations in the region. As a result, hazards at other locations have not been considered in the REDARS™ 2 analyses for this project.
- ***Task 3. REDARS 2 Analysis,*** Under Task 3, the REDARS™ 2 software has been used together with the input data from Task 1 and the seismic hazards results from Task 2 in order to conduct the analysis of the seismic risks to the SC highway system due to the Golden Guardian scenario earthquake. This task has involved: (a) use of default component vulnerability models built into REDARS™ 2 to estimate damage states to the system's bridges, and highway pavements; (b) use of default repair models built into REDARS™ 2 to estimate repair costs and downtimes of the damaged components at various post-earthquake times; (c) use of these post-earthquake downtimes to assemble a series of region-wide highway system states that, at particular post-earthquake times, indicate which roadway links throughout the system are closed to traffic and which links are open; (d) application of REDARS™ 2 network analysis procedures to these various post-earthquake time-dependent system states in order to estimate earthquake-induced traffic flow reductions, travel time increases, and trip demand reductions at each post-earthquake time; and (e) use of these

results, together with component repair costs estimated earlier, in order to estimate direct economic losses due to earthquake damage to the region's highway system.

1.4 REPORT ORGANIZATION

The remainder of this report is organized into the following four main chapters:.

- ***Chapter 2. Seismic Risk Analysis Methodology.*** Chapter 2 summarizes the main features of the REDARS™ 2 methodology for seismic risk analysis (SRA) of highway systems that has been applied under this project, and describes the various models used within REDARS™ 2 to estimate component damage states and repair requirements, and post-earthquake traffic flows, travel times, and trip demands throughout the highway system.
- ***Chapter 3. Data Compilation.*** Chapter 3 describes our development of the input data used to characterize the SC highway-roadway system, the bridges and other components throughout the system, and the trip demands on the system.
- ***Chapter 4. Analysis Results.*** Chapter 4 describes the results of the REDARS™ 2 SRA of the SC highway system. These results include the bridge and roadway damage states due to the GG scenario earthquake, the corresponding highway-roadway system states at various post-earthquake times, the travel time increases and trip demand reductions at each of these post earthquake times, and the economic losses due to these traffic/travel impacts and component repair costs.
- ***Chapter 5. Concluding Comments.*** Chapter 4 summarizes the procedures and results from the preceding chapters, and provides our interpretations and recommendations pertaining to these results.

CHAPTER 2
SEISMIC RISK ANALYSIS METHODOLOGY

2.1 OVERVIEW

REDARS™ 2 is a methodology and software package for SRA of highway systems nationwide. It has been developed to provide state transportation agencies and the engineering and academic community with a technically sound and practical approach for addressing the all-important issues of highway system resiliency and performance after a major earthquake that are discussed in Section 1.1. It is intended to serve as a decision-guidance tool for: (a) pre-earthquake planning of engineering and emergency-response measures for improving the seismic performance of highway systems; and (b) post-earthquake emergency response in real time. The REDARS™ 2 methodology and software are described in detail elsewhere (e.g., Werner et al., 2006) and are summarized in the remainder of this chapter.

REDARS™ 2 can be applied either probabilistically or deterministically. For probabilistic SRA, REDARS 2 develops multiple simulations, in which each "simulation" consists of a complete set of system SRA results for one set of randomly selected input and model parameters. The input and model parameters for one simulation may differ from those for other simulations because of random and systematic uncertainties. For each simulation, geoseismic, geotechnical and structural earthquake engineering, repair/construction, transportation network, and economic models and procedures are used to estimate:

- ***Seismic Hazards.*** Ground motions and permanent ground displacements (PGDs) due to liquefaction and surface fault rupture at the site of each component in the highway system.

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

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

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

The REDARS™ 2 deterministic analysis procedure (as carried out under this Golden Guardian (GG) exercise) is identical to the above analysis procedure for each simulation of a probabilistic SRA except that now, the analysis uses a single set of median or average input and model parameters, rather than a randomly selected set of parameters.

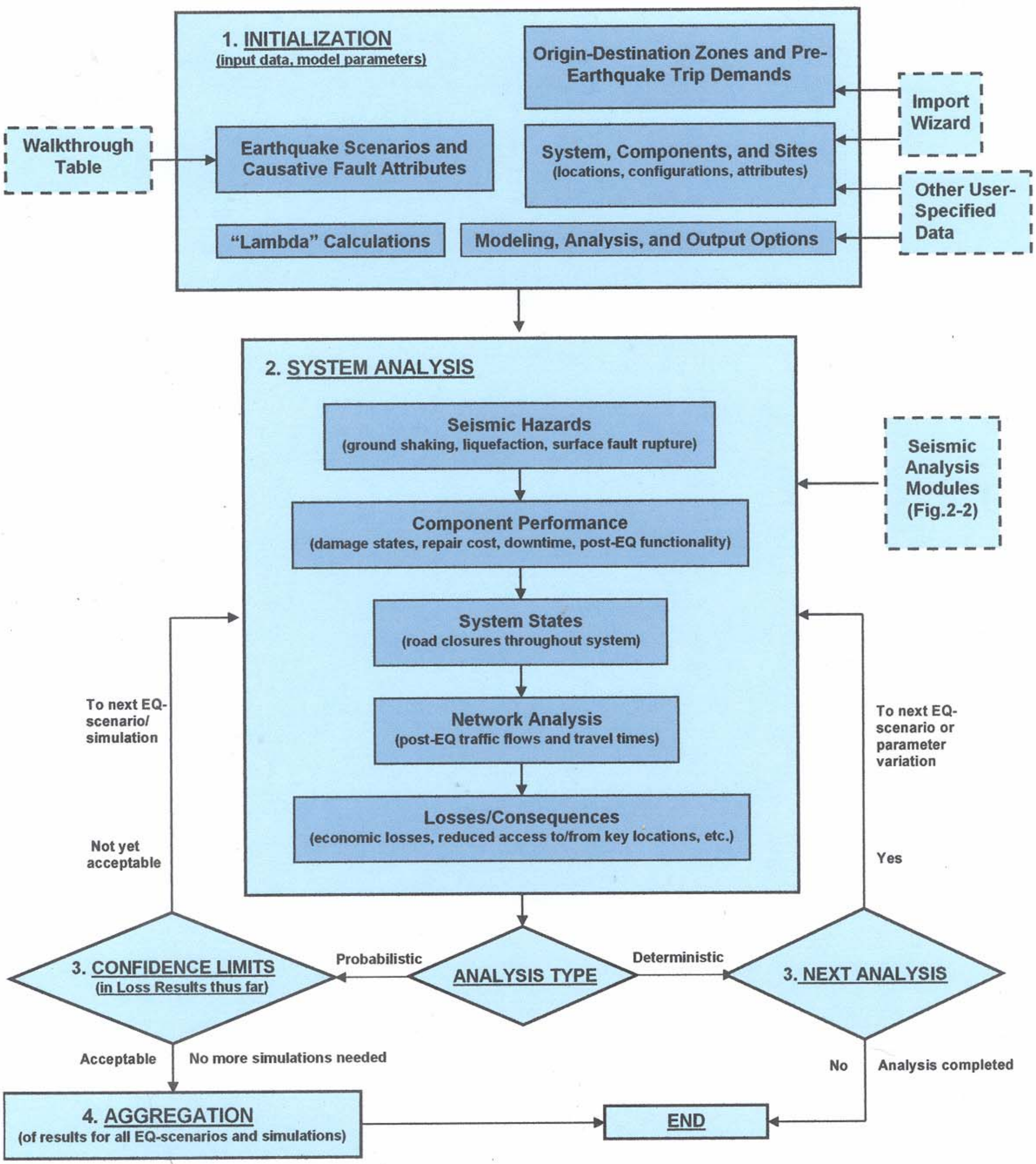


Figure 2-1. REDARS™ 2 Methodology for Seismic Risk Analysis of Highway Systems

2.2 FEATURES

This REDARS™ 2 SRA methodology has the following desirable features.

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

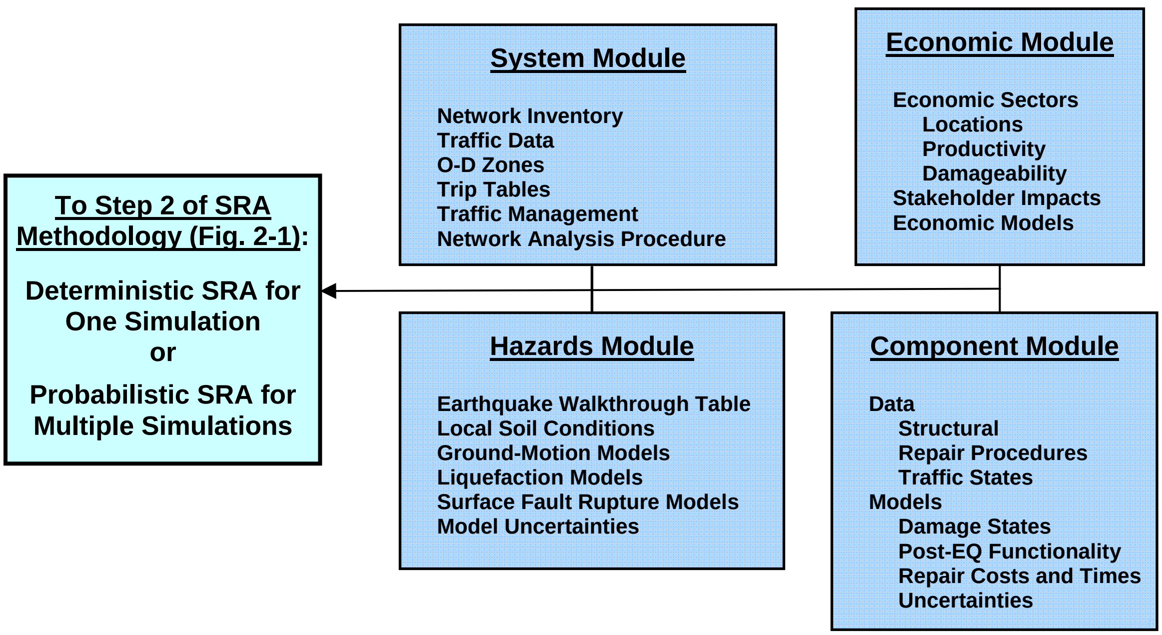


Figure 2-2. REDARS™ 2 Seismic Analysis Modules

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

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

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

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

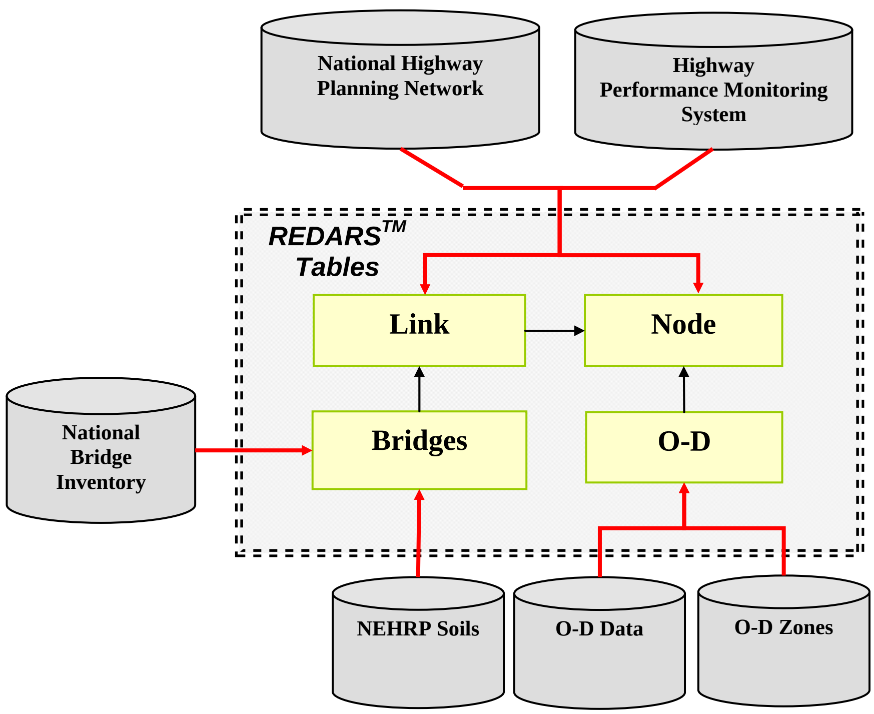


Figure 2-3. Development of REDARS™ 2 Input Data from Publicly Available Databases

2.3 SEISMIC ANALYSIS MODULES

The four REDARS™ 2 seismic analysis modules that are shown in Figure 2-2 are described in the remainder of this section. These descriptions include a summary of the general features of each module and, then, how the module is applied and used in this Golden Guardian (GG) project analysis.

2.3.1 <u>Hazards Module</u>

2.3.1.1 Overview

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

REDARS™ 2 currently computes site-specific seismic hazards in the following ways:

- For a given earthquake from the walkthrough table or any other earthquake with a user-specified magnitude and location, ground motion attenuation models built into REDARS™ 2 are used to compute site-specific ground motions. REDARS™ 2 will eventually include a library of state-of-knowledge attenuation models for estimating ground motions hazards throughout the United States. Currently, two such models are included in REDARS™ 2 – the Abrahamson-Silva (1997) model for computing ground motions from crustal earthquakes in the Western United States, and the Silva et al. (2002) model for computing ground motions from earthquakes in the Central and Eastern United States. In the future, more recent models will be incorporated into REDARS™ 2, such as the models from the Next Generation Attenuation (NGA) research program (Abrahamson et al., 2006).
- REDARS™ 2 can also accommodate ground motions defined by ShakeMap-type maps of spatially distributed ground motion shaking intensities. Such maps may be developed in real time after an actual earthquake or may represent estimated ground motions from hypothetical scenario earthquakes (http://earthquake.usgs.gov/shakemap) . In this GG project, ShakeMap representations of the ground shaking hazards from the project's scenario earthquake have been directly input into REDARS™ 2.
- REDARS™ 2 currently uses the Youngs et al. (2003) and the Bardet et al. (2002) models to estimate site-specific permanent ground displacements (PGDs) due to surface fault rupture and liquefaction hazards respectively. As for ground shaking hazards, the modular feature of the REDARS™ 2 software will enable new and updated models of such hazards as they are developed under future research and development programs.

2.3.1.2 Hazard Estimation under This Project

Under this project, ShakeMaps developed by USGS were used to represent ground motion hazards throughout SC were due to the Magnitude 7.8 scenario earthquake considered in the project. In addition, shapefile representations of PGD distributions along the length of the

[1] ShakeMap is a product of the USGS Earthquake Hazards Program in conjunction with seismic network operators. ShakeMap ground motion maps can be generated in real time for actual earthquakes in Northern and Southern California, the Pacific Northwest, Nevada, Utah, and Alaska. In addition, ShakeMap ground motion estimates for various hypothetical earthquakes and from actual prior earthquakes are available.

ruptured segment of the San Andreas Fault were used to represent the hazards from surface fault rupture. In addition, shapefiles and data tabulations provided by the California Geologic Survey were used to estimate landslide and liquefaction hazards along various roadways within the study area. These hazards are further described in Section 4.1.

2.3.2 Component Module

2.3.2.1 Overview

The Component Module contains input data and models for estimating the seismic performance of each component in the highway system. The following estimates are developed:

- Component damage-state models estimate the degrees, types, and locations of the damage to each component in the system due to the seismic hazards estimated by the models in the Hazards Module.
- Repair models then estimate how each component's damage will be repaired, how much the repairs will cost, how long they will take, and the component's traffic states (i.e., whether it will be fully closed, partially open, or fully open to traffic) as the repairs proceed over time after the earthquake.

These damage state and repair estimates can be developed by applying either default models that are built into REDARS™ 2 or user-specified models that the user can input into REDARS™ 2 for any component(s) in the system. Default models provide first-order estimates of component damage states as well as repair requirements. For bridges and tunnels, they are provided as probabilistic fragility curves, which can also be used to develop deterministic damage estimates by using median values of structural capacities represented by these curves. Default repair models for bridges and tunnels are deterministic, as are models for estimating damage and repair requirements for approach fills and roadway pavements. These models are summarized in Section 2.3.2.2 and are described in more detail in Werner et al. (2006).

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

User-specified models for bridges will provide more refined seismic-performance estimates than will the default models. Therefore, they are most appropriate for modeling of bridges that: (a) have unique geometries and/or structural attributes; (b) are located along routes that are non-redundant or are critical to post-earthquake response; or (c) will have a large impact on traffic flows over a significant portion of the highway system, if they are severely damaged. However, the development of user-specified models for an individual bridge, which would require detailed seismic analysis of the structure that would be conducted by the user outside of REDARS™ 2, can be time consuming. Therefore, it is impractical to develop such models for most of the large number of more “typical” bridges that comprise a highway system. For such bridges, the default models are much more feasible to implement. Development of improvements to current default bridge models 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. These models are summarized in Section 2.3.2.2, and are future described in Werner et al. (2006).

2.3.2.2 Hazard Estimation under This Project

In this project REDARS™ 2 has used built-in default models to estimate damage states and repair requirements of bridges and highway pavements throughout the SC highway system. These models are briefly summarized below, and are described in more detail in Werner et al. (2006).

2.3.2.2.1 Bridge Damage States due to Ground Shaking

An initial version of the REDARS™ 2 default model for estimating bridge damage due to ground shaking was developed by Mander and his associates (Dutta and Mander, 1998; Mander and Basoz, 1999). This approach, which uses a nonlinear capacity-spectrum procedure to estimate bridge damage, has been incorporated into the HAZUS-SR2 methodology for estimating earthquake-induced losses to the built infrastructure throughout the United States (FEMA, 2002). The main elements of this approach are as follows:

- This is a simplified approach that is developed from principles of mechanics in order to rapidly estimate damage states for large populations of bridges within a region-wide highway system. The HAZUS damage state definitions used in this approach are shown in Table 2-1.

Table 2-1. Bridge Damage States (FEMA, 2002)

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

- This approach was developed for application to bridges nationwide. Therefore, by necessity, it is based on the data in the National Bridge Inventory (NBI) database, which is the only available electronic database of attributes for bridges throughout the country (FHWA, 2003). However, the database was developed for bridge-maintenance uses and therefore does not include many bridge structural attributes that are relevant to seismic-response analysis.
- In this approach, capacity spectra are developed for several types "standard bridge" construction used throughout the United States. These spectra account for: (a) the inelastic strength and deformation capacity of the bridge piers, including the effects of strength loss due to cyclic motion; (b) damage limit states; and (c) the contributions of the deck to the bridge's overall capacity, in terms of three-dimensional (3D) deck arching/membrane action.
- Each bridge in the highway system is assigned to one of these "standard bridge" types, based on data for that bridge that are obtained from the NBI database. Then, the "standard bridge" capacity spectrum for that bridge is modified to account for various bridge-specific attributes from the NBI database that are related to skew and 3D deck membrane/arching action. Table 2-2 shows how various fields in the NBI database are used to infer bridge capacity spectra.

Table 2-2. Use of NBI Data Fields to Infer Bridge Performance (Mander and Basoz, 1999)

NBI Data Item	Definition	Use in Inferring Bridge Fragility
1	State *(STATE)*	To infer seismic design code used.
8	Structure Number	General ID Number.
27	Year Built *(YEAR)*	To infer whether seismic or conventional design.
34	Skew *(ANGLE)*	To compute capacity modification factor that accounts for skew
42	Service Type	To select highway bridges (e.g., rather than rail or pedestrian bridges) from NBI database.
43	Structure Type *(ITYPE)*	To infer which type of "standard" bridge to use as basis for fragility curve development.
45	Number of Spans in Main Unit & Approach Spans *(NSPAN)*	To infer whether single- or multiple-span bridge.
48	Maximum Span Length *(SPNMAX)*	To also infer if bridge is a major bridge (as defined in NBI (2002).
49	Structure Length *(SLGTH)*	To infer average span length, and to compute replacement value.
52	Deck Width *(BDECK)*	To compute replacement value.
54	Minimum Vertical Underclearance *(MINVUC)*	To infer default value of approach-fill thickness (if accurately specified in FEMA, 2003).

- From this, structural capacities leading to the onset of each of the damage states listed in Table 2-1 are characterized in terms of limit state values of the spectral acceleration at a natural period of 1.0 sec. for most bridge types and damage states. For some bridge types and damage states where short-period response will be most important, the spectral acceleration at a period of 0.3 sec. is used.
- For a given set of demand ground motions, a bridge's damage state is determined by comparing the demand value of the spectral acceleration (at a period of 1.0 sec. or 0.3 sec.) to the limit-state spectral-acceleration value leading to the onset of each damage state. In this, uncertainties in the seismic demands (site-specific ground motions) and the bridge's structural capacity (limit state spectral acceleration for each damage state) are considered.

In the course of our research to develop the REDARS™ 2 methodology and software for SRA of highway systems, development project for FHWA-MCEER and our REDARS™ demonstration project for Caltrans, we incorporated the following modifications to the approach as it appears in HAZUS:

- The approach did not account for the beneficial effects of jacketing of bridge columns, which is a common and effective approach for seismic retrofit of bridges in California and other earthquake-prone regions of the country. Therefore, to approximate these effects, we incorporated capacity-enhancement factors for column-jacketed bridges that were developed by Shinozuka (2004) into the above capacity-spectrum approach.
- We carried out a validation application of this approach by using it to estimate bridge damage throughout the greater Los Angeles area due to the 1994 Northridge Earthquake, and compared these estimates to post-earthquake bridge damage observations. From this, we found that the approach substantially overestimated that extent of the region-wide bridge damage from this earthquake. Therefore, we modified the structural capacities in the HAZUS model to improve the comparisons between the predicted and observed bridge damage states from this earthquake. This validation of the REDARS™ 2 default bridge model is described in detail in Werner et al. (2006).

2.3.2.2.2 Repair of Bridge Damage

The REDARS™ 2 default model for repair of earthquake-damaged bridges is based on the assumptions listed below. :

- *California-Based Model.* The repair model was developed in collaboration with senior bridge engineering and maintenance staff 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.
- *Qualitative Damage-State Descriptors.* The model is based on the qualitative damage-state descriptors listed in Table 2-1. Unfortunately, these descriptors do not provide information on the types, extents, and locations of earthquake damage throughout the bridge with a level of detail that would ordinarily be needed to estimate overall bridge repair requirements. There is a well-recognized need for research to develop updated bridge damage estimation models that include improved damage descriptors for estimation of repair requirements.

- *Repair Consequences and Strategies.* Table 2-3 lists the general repair consequences and strategies that are assumed for each damage state listed in Table 2-1.

Table 2-3. Assumed Repair Consequences and Strategies for Each Bridge Damage State

Damage State (Table 2-1)	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.

- *Availability of Repair Resources.* When a region is subjected to a very large earthquake that causes widespread damage to many elements of the region's infrastructure (e.g., to its buildings, power systems and other lifelines, as well as the highway system) there could be competition for repair resources (labor, materials, and equipment), particularly if such readily available resources are insufficient to accommodate all of the damage-repair demands. This situation is particularly relevant to this GG exercise, and the very large scenario earthquake that is being considered. The REDARS™ 2 default bridge repair model assumes that resources for repair of all of the damaged bridges throughout the region can be rapidly mobilized, and that shoring and repair of all of these bridges can begin without delays.

- *Accessibility of Bridge Damage.* It is assumed that all elements of the damaged bridges will be readily accessible for repairs. For any bridges that cross major rivers or have other accessibility constraints, the repair costs and times provided in this default repair model could underestimate actual repair requirements.

- *Underlying Roadways.* If a damaged bridge crosses over an underlying roadway, this default bridge repair models 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; i.e., once the bridge is shored, it is assumed that the underlying roadways will be fully open to traffic.

- *Non-Roadway Infrastructure.* Experience from past earthquakes has shown that post-earthquake bridge traffic 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 bridge traffic are neglected in this repair model.
- *Emergency Repairs.* After the Northridge Earthquake, Caltrans implemented a special emergency strategy for replacement of collapsed bridges along freeways that were essential to the recovery of the surrounding region. This consisted of a bonus-incentive program that increased replacement costs but substantially reduced bridge downtimes which, in turn, substantially reduced the time needed to restore normal traffic operations along these freeways. Such emergency repair strategies are not considered in the REDARS™ 2 default repair model; i.e., it is assumed that repairs are carried out under non-emergency conditions.

The default repair model that was developed in accordance with the above assumptions is shown in Tables 2-4 (traffic states) and 2-5 (repair costs). It is noted that this default model can be easily overridden, if the user wishes to consider effects of availability of repair resources, damage accessibility, underlying roadway lane blockage during repair of an overlying damaged bridge, traffic impacts of damage to non-roadway infrastructure, and emergency repair strategies.

Table 2-4. Default Traffic States during Repair of Bridge Damage from Ground Motions (Werner, et. al., 2006)

Bridge Damage State (Table 4-1)	Number of Bridge Spans	Post-Earthquake Traffic State:			
		Bridge		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%
Complete:	≤ 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 2-5. Default Bridge Repair Costs (Werner et al., 2006)

Damage State Designation (Table 4-1)	Best Estimate Repair-Cost Ratio (*RCR*)[1, 2]
None	*RCR* = 0.0
Slight	*RCR* = 0.03
Moderate	*RCR* = 0.25
Extensive	*RCR* = 0.75
Complete	*RCR* = 1.0

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

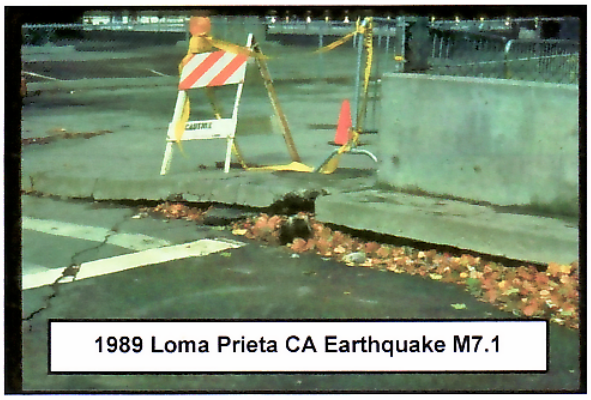
2 Bridge replacement cost *(REP)* is computed as the product of a unit replacement costs (in dollars/ft^2) and the surface area of the bridge in ft^2 (defined as the product of the total bridge's length and its width.) The default replacement cost in this repair model is assumed to be \$150/ft^2, which 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.

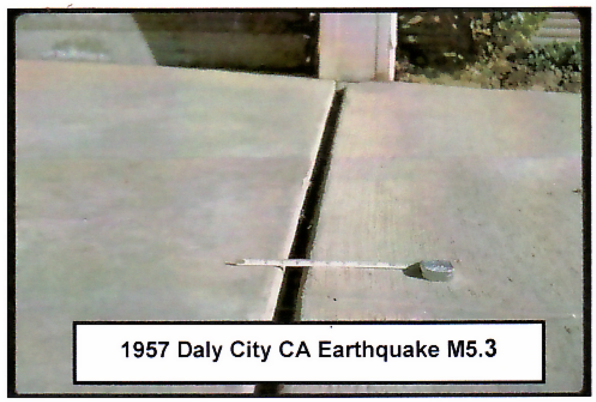
2.3.2.2.3 Damage State and Repair Models for Highway Pavements subjected to Fault Rupture and Landslide Hazards

The REDARS™ 2 default model for highway pavements subjected to PGD is based on the judgment and recommendations of senior Caltrans staff members who are familiar with pavement construction, maintenance, and repair practice in California. It is based on the same general assumptions as listed for the bridge repair model in Section 2.3.2.2.2. Under this project, this default model has been used to characterize the seismic performance and associated repair costs and post-earthquake traffic states for pavements subjected to PGD due to surface fault rupture and landslide. Table 2-6 provides this model, and Figure 2-4 shows examples of damage levels and types that are assumed to be associated with each highway-pavement damage state designation on which this model is based.

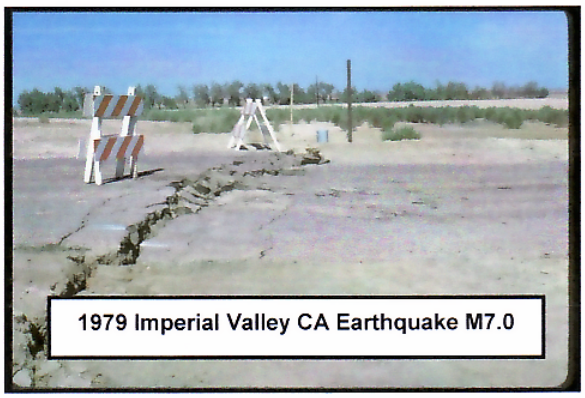
Table 2-6. Default Earthquake Repair Model for Highway Pavements and Subsurface Materials

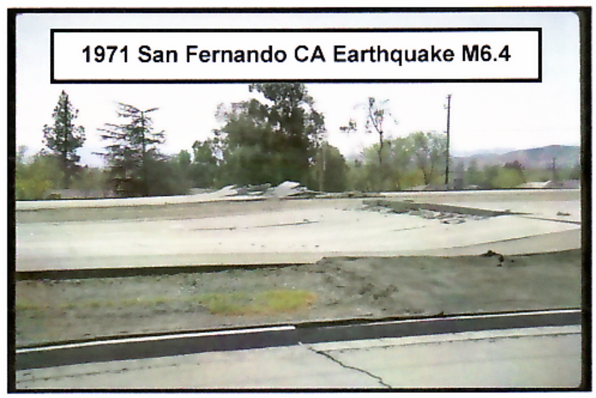
Damage State				Traffic State		Repair Costs (per lane-mile)
REDARS™ Designation	Permanent Ground Displacement, inches.	Description (see Figures 1 through 4)	Repair Procedure	Days after EQ (incl. mobilization time)	Lanes Available (% of Pre-EQ lanes)	
1 (None)	< 1 in.	No repairs needed	None	0	100%	$0
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)



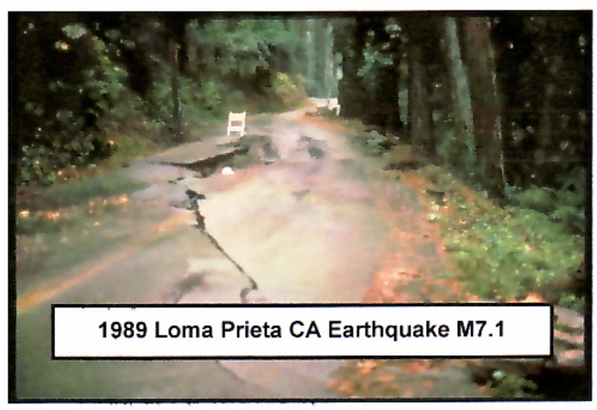


a) Damage State 2 (No closure to traffic. Minor repairs carried out during off hours)





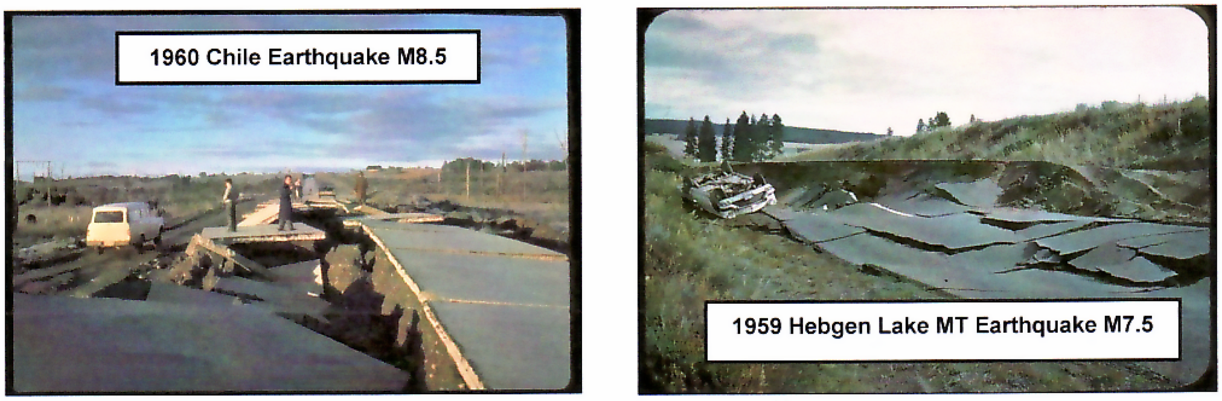
b) Damage State 3 (Closed to traffic for 2-3 days for repair of moderate pavement damage. No subbase damage)



c) Damage State 4 (Pavement structure has failed and must be rebuilt, and soils have deformed. Closure for 7 days)

Figure 2-4. Highway Pavement Damage State Examples Part 1 of 2 (Werner et al., 2006)

(All Photographs courtesy of Earthquake Engineering Center Research Library, University of California at Berkeley, Richmond CA)



d) Damage State 5 (Total failure requiring reconstruction of pavement and underlying soils. Closure for 7 weeks)

Figure 2-4. Highway Pavement Damage State Examples Part 2 of 2 (Werner et al., 2006)
(All Photographs courtesy of Earthquake Engineering Center Research Library, University of California at Berkeley, Richmond CA)

2.3.2.2.4 Model for Removal of Landslide-Induced Debris from Highway Pavements

As noted in Section 2.3.1.2, landslides can damage highway pavements from PGD due to sliding of the underlying soil materials, and can also deposit debris on the roadways if the overlying hillsides happen to slide. Experience from past earthquakes has shown that, if substantial volumes of debris are deposited onto a roadway, the roadway could be closed to traffic for some time until the debris can be removed. For example, during the 1989 Loma Prieta Earthquake, substantial volumes of landslide-induced debris were deposited on Highway 17 – a major highway that connects San Jose and Santa Cruz CA. This highway was closed for about 2 months until this debris could be removed and the hillside could be repaired.

As part of this overall project, the California Geological Survey (CGS) has estimated that substantial earthquake-induced sliding could occur within the Cajon Pass and the San Gorgonio Pass, leading to deposits of debris on the highways within these passes. To estimate times to remove this debris, we contacted senior Caltrans staff who have extensive experience with landslides and the removal of landslide-induced debris. Based on the experience and judgment of these Caltrans staff, a debris-removal model was developed that is summarized below.

a) Factors affecting Debris-Removal Times.

During our discussions, the Caltrans staff members identified the following factors that could affect landslide debris-removal times.

- <u>Contractor and Truck Availability</u>. After a major landslide, debris access and removal is accomplished by Caltrans' brokering of landslide-removal work to many different contractors that can come to the slide from a broad area. These contractors will all hire as many trucks and drivers as possible, and will direct them to the landslide site. In addition, as much debris-removal equipment (e.g.., backhoes) as possible will be mobilized at the landslide site. Caltrans' experience during past major landslides has shown that many contractors and trucks can be mobilized during the same day as the event. During a great earthquake of the size considered here by USGS, this process will be facilitated by state and federal disaster declarations, which will eliminate all permit issues[2].

- Access to Landslide Site. Debris removal times will be affected by the ability of trucks to access the landslide site. If access is difficult (e.g., due to damage to highways or other elements of the built infrastructure), debris removal times could be slowed. Also important is whether trucks can access the slide from one side or both sides of the slide area. If trucks access to both sides of the slide can occur, debris removal times will be shortened.
- Debris Hauling Distance. A third factor affecting debris removal times is the distance from the landslide to the dump site where the trucks unload the debris from the slide. If the landslide is in an environmentally sensitive area or a residential area, the dump site may need to be relatively far from the landslide site. This will lengthen the total debris-removal time.

b) Debris Removal Model

The estimation of the times needed to remove earthquake-induced landslide debris from the highways in the Cajon Pass and San Gorgonio Pass areas will assume that: (a) sufficient contractors and trucks and equipment can be rapidly mobilized at the landslide sites; and (b) the debris hauling distances are all short.

From this, it is assumed that roughly 5,000 yd^3 of debris can be removed if the slide area can be accessed by trucks from one side only, and that approximately 10,000 yd^3 of debris can be removed if the slide area can be accessed by trucks from both sides of the slide.

In Chapter 4, these assumptions are used to estimate debris removal times for the landslides in the Cajon Pass area and for one of the landslide scenarios along the San Gorgonio Pass.

2.3.3 System Module

2.3.3.1 Input Data

As noted in Chapter 1, a major effort under this project focused on the development of highway-network data and origin-destination trip-table data for the multiple SC counties that are included in the study area. This effort is summarized in Chapter 3.

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[2] However, it should be recognized that the Magnitude 7.8 earthquake considered in this USGS exercise will cause damage extending over a very large area, and that this damage will not be limited to the highway system. Significant damage to buildings, utilities, and other elements of the region's built infrastructure will also occur. This can result in a widespread demand and possible competition for repair resources that, at least initially, could slow the mobilization of these resources to many of these damaged infrastructure elements.

2.3.3.2 Network Analysis Model

REDARS™ 2 uses a variable-demand network-analysis model that accounts for the dependence of system-wide travel times and trip demands on traffic congestion. This section summarizes the basic concepts behind this model. A more detailed description of the model is provided in Moore et al. (2006) and Werner et al. (2006).

2.3.3.2.1 Statement of the Problem

A user-equilibrium model with fixed trip demands was included in the initial beta version of REDARS™. Such fixed-demand models (FDMs), which are widely used in current transportation planning practice, presume that individual user travel times on all routes actually used are equal to or less than user travel times that would be experienced on any unused route. That is, each (perfectly informed) user will choose the route that minimizes his/her travel time.

However, results from a validation of this model against observed traffic flows after the Northridge Earthquake show that this model can produce inadequate estimates of travel times if system traffic-carrying capacities are severely reduced due to a major natural-hazard or man-made hazard event (Cho et al., 2006). For example, according to local traffic reports obtained one day after the earthquake observed traffic volumes doubled on roads near collapsed bridge sites (i.e., near the bridge collapses at I-10 / La Cienega, SR-118/ Gothic, and I-5/SR-14) (Caltrans, 1995). Under these conditions, the observed travel-times along these roads increased by only 15 minutes per trip relative to pre-earthquake travel times. However, when the user-equilibrium model with fixed trip demand was used to predict post-earthquake travel time along these same roads, the model over-estimated travel time by as much as a factor of 10.

One reason for this result is that the FDM assumes inelastic (i.e., fixed) trip demands; i.e., post-earthquake trip demands on the system are assumed to be equal to pre-earthquake trip demands, regardless of the extent of the earthquake damage to the system. However, this assumption is implausible under conditions of substantially reduced network capacity and corresponding increased traffic congestion. For this situation, observed data has shown that many travelers are unwilling to endure such travel time delays and will instead forego their trip.

2.3.3.2.2 Model Concepts

To address this problem, a new variable-demand model (VDM) was formulated and programmed into REDARS™ 2 to replace the fixed-demand model. This model accounts for the tendency of rip demands to decrease as the traffic congestion within the highway system increases (e.g., due to roadway closures caused by earthquake damage to the system).

As noted above, the FDM assumes that trip demand associated with zone-to-zone travel is inelastic; i.e., it does not vary with travel time. Under these conditions, all drivers continue to attempt travel, even if a trip takes several hours and has an unreasonable social cost. Figure 2-5 illustrates the social cost of a hypothetical earthquake under this situation. If the traffic-carrying capacity is reduced due to earthquake damage, the congestion will increase. The network capacity (or supply) is reduced from S_1 to S_2, and the fixed trip demand is represented by D_1.

The corresponding travel costs are P_1 and P_2 respectively, and the social cost (i.e., the value of time due to increased travel time on the roadway and the value of trips foregone) is $(P_2 - P_1) * D_1$.

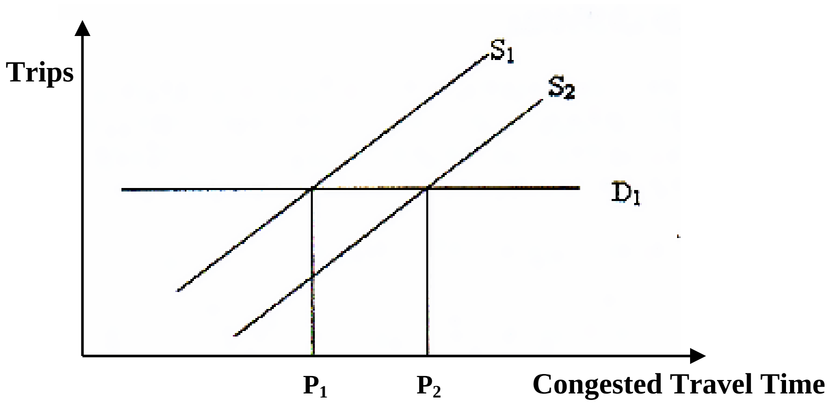


Figure 2-5. Fixed-Demand Model for an Earthquake-Damaged Highway System

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

Figure -2-6 illustrates the resulting effects of variable trip demand, as characterized by the VDM. This figure shows that before an earthquake, the highway system would provide a capacity of S_1, and the travel demand (D_1) on this network would result in an equilibrium travel time of P_1. After an earthquake, the capacity would be reduced to S_2, and the travel demand D_2 would result in a travel time of P_2'. The resulting social cost of this reduction in network capacity is given by the expression $[(P_2' - P_1) * D_2] + [(P_2' - P_1) * (D_1 - D_2)/2]$, and will be much lower than the cost predicted by the FDM.

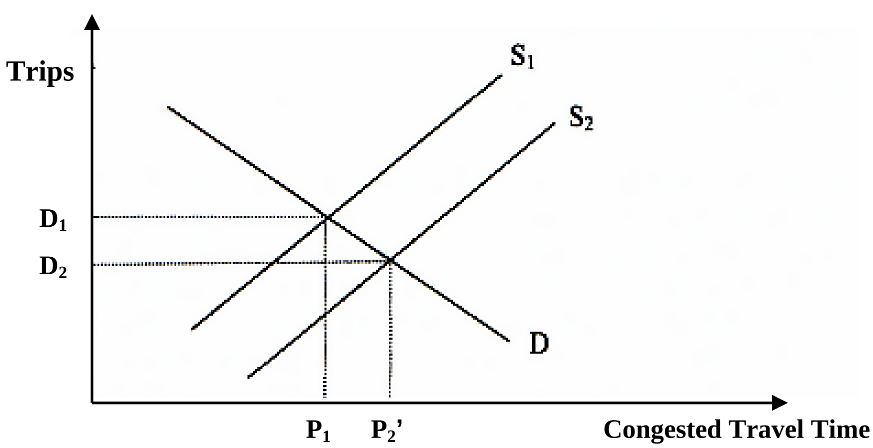


Figure 2-6. Variable-Demand Model for an Earthquake-Damaged Network

2.3.3.2.3 Other Features of Network Analysis Model

Other features of the REDARS™ 2 network analysis models summarized below:

- *Minimum-Path Algorithm.* In the initial beta version of REDARS™, route choice in accordance with a FDM was estimated by the Moore-Pape algorithm, which attributes nodes according to the travel time from an origin (Moore, 1957; Pape, 1974). In REDARS™ 2, the Moore-Pape algorithm was replaced by the less computationally intensive dual-simplex algorithm, detailed by Florian et. al. (1981). The increased computational efficiency of this model is due to the model's ability to take advantage of the fact that two paths built from two adjacent root zones often share common links). 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.
- *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 for all types of trips accommodated by the highway system (e.g., for automobile trips, various types of freight trips, etc.). However, these various trip types will typically have different origins and destinations within the region served by the highway-roadway system, and will also 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.

2.3.4 Economic Module

The Economic Module contains a first-order model for estimating repair costs and economic losses due to increased travel times and reduced trip demands. In this model, repair costs are estimated from the repair model for bridges and roadway pavements that is summarized in Section 2.3.2.2 (see Tables 2-5 and 2-6). The estimation of economic losses due to travel time increases and trips foregone is an extension of an approach used by Caltrans to estimate economic losses due to disruption of the Los Angeles area highway system due to the Northridge Earthquake (Caltrans, 1995). It uses unit losses that represent the cost (in units of dollars per hour per passenger-car-unit) of the travel time delays and trips foregone. These unit losses consider such factors as vehicle occupancy rates, freight-trip dollar value, fuel costs, and cost of excess fuel, and will also depend on the type of trip (e.g., automobile, freight type 1, freight type 2, etc.). The default unit looses that are currently used in REDARS™ 2 are based on data for the greater Los Angeles area that were developed from traffic congestion statistical analyses by the Rand Corporation of California (see website http://ca.rand.org). From this, default unit losses of $13.45/(pcu-hour) for automobile trips and $71.05/(truck-hour) for truck trips have been adopted[3]. These default values can be readily overridden by a REDARS™ 2 user if desired.

[3] The quantity "pcu" is a unit of traffic flow and refers to "passenger car unit". An automobile is assumed to represent 1 pcu and a truck is assumed to represent 3 pcu.

Broader economic impacts of earthquake-induced travel-time increases and reduced trip-demands (i.e., their effects on businesses, stakeholders, and the regional and national economy) are not included in this loss model. However, in a companion project under this USGS program, results from the REDARS™ 2 network analysis will be translated into data that a regional Input-Output model for estimating such economic impacts can use (Cho, 2007).

CHAPTER 3
DATA COMPILATION

3.1 BACKGROUND

This chapter describes some of the key issues associated with data compilation for this Golden Gate (GG) exercise and the approach used to address these issues. REDARS™ 2 is designed to analyze transportation system data in the database form shown in Figure 3-1. The database structure was designed to analyze seismic risks to a transportation system with minimal data requirements. In a general case, users will download the required data from different federal and public websites, and incorporate these data into the REDARS™ 2 Import Wizard to automatically create the database for the region of interest (see Cho, et. al., 2006a for details).

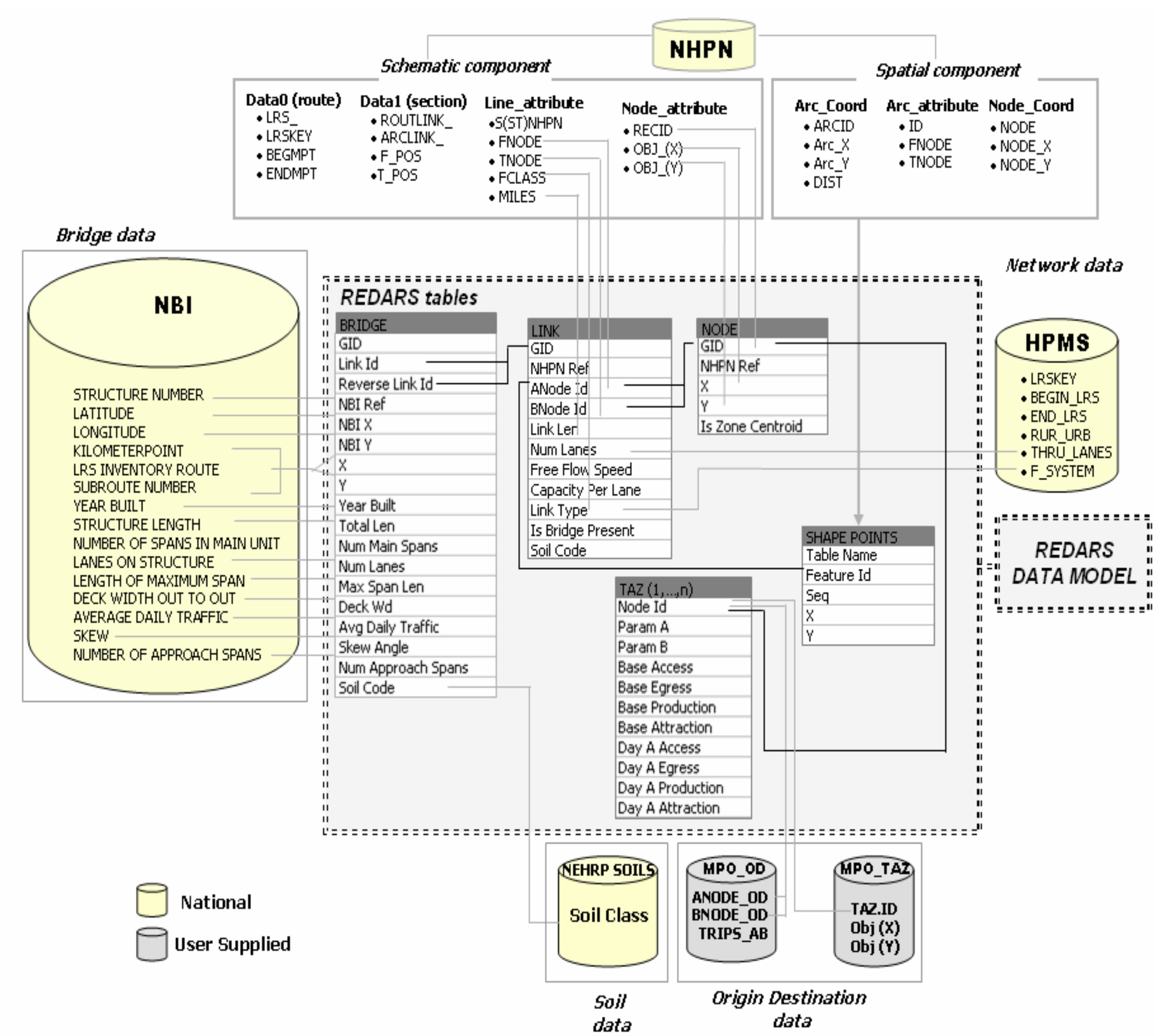
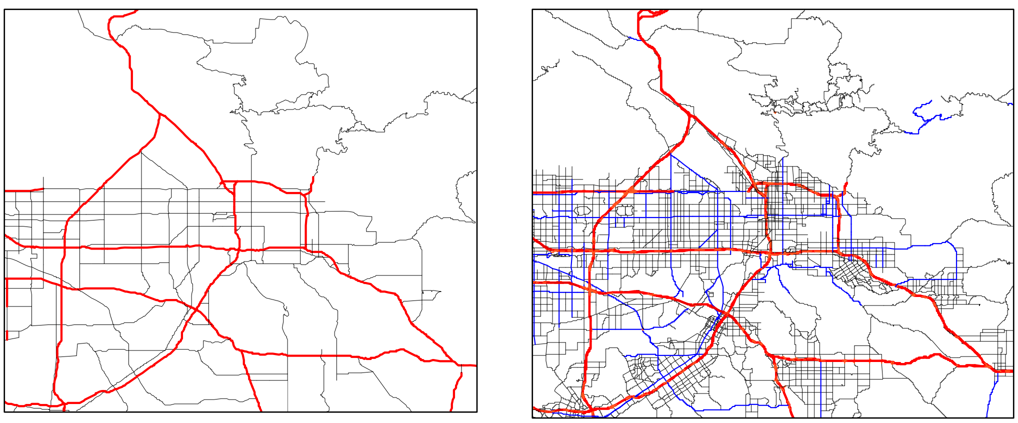


Figure 3-1 REDARS™ 2 Data Model (Cho et al., 2006)

However, in this GG exercise, the Import Wizard could not be used because of conditions related to network detail, network extent, and database size that are summarized below. Therefore, the transportation system database was created manually as described in Section 3.2.

- ***Network Detail.*** The Import Wizard uses the National Highway Planning Network (NHPN) and Highway Performance Monitoring System (HPMS) databases to model the spatial configuration and attributes of the highways and roadways in the SC study area. These national databases include highways and major arterials only and do not include local roadways. However, the very large scenario earthquake considered in this GG exercise is estimated to cause significant damage to bridges in the study area, which in turn, will close certain sub-regions of the highway system. Without consideration of local roadways, primarily as alternative routes for disrupted freeways and major arterials, the simplified network data included in the national databases would result in highly overestimated impacts. In reality, drivers would select detour routes that would require driving longer distances; while the model would assume that drivers would stay at home because no open roadways would be available. For this reason, the analysis in this study was performed using detailed transportation network data provided by the two cognizant local metropolitan planning organizations (MPOs) for the study area -- the Southern California Association of Governments (SCAG) and the San Diego Association of Governments (SANDAG) -- which include local roadways. Figure 3-2 compares network data from federal sources and the local MPOs in the vicinity of the I-10 and I-215 intersection,



(a) FHWA Network Data (b) SCAG Network Data

Figure 3-2 Comparison of Network Data by Data Source

- ***Network Extent.*** As noted above, the project study area extends across the jurisdictions of two MPOs -- SCAG (which includes Ventura, Los Angeles, Orange, San Bernardino, Riverside, and Imperial Counties) and SANDAG (which includes San Diego County). Therefore, the data from each MPO had to be *stitched* together into one seamless database, which could not be accomplished through the Import Wizard. Since the operability of the I-10 and I-15 highways near the San Andreas Fault is one of main concerns in this scenario, the data should provide alternative routes (such as I-8 or Pacific Coast Highway) in the event that both the I-10 and I-15 highways are closed. To maintain the connectivity through I-8 and I-5 through San Diego County, transportation network data from SANDAG was "joined" with the SCAG network data, through common nodes in both network data sets.

- ***Database Size.*** The size of database for this study area that was initially obtained from the MPOs was too large to be directly used in REDARS™ 2. Therefore, a reduced database was created manually by using expert judgment on what datasets to use and how to consolidate the data in order to reduce the overall database size. REDARS™ 2 uses the Microsoft JET OLEDB Engine to manage its databases through a Microsoft Database (MDB) file format. Although this is a common and stable database management system in Windows-based PCs, its data integrity sometimes becomes unstable when large datasets are imported; i.e., a database file cannot be larger than 2 gigabytes. The initial dataset that was created for this project included 6,353 bridges, 55,262 nodes, 156,708 uni-directional links (with 3,427,466 points that present line geometries), and two 8791-by-8791 trip origin-destination (OD) matrices (for passengers and freights, double precision). This initial database file was beyond the limit of the current REDARS™ 2 software. We eventually used all the network and highway component data (i.e., all nodes, links, and bridges listed above), but adopted a reduced OD matrix to SCAG area, which was a 4191-by-4191 combined OD trip matrix of passenger and freight, double precision. The trips from/to San Diego County from the SCAG area were incorporated as boundary conditions in the OD matrix.

3.2 DATABASE CREATION

Figure 3-3 shows the steps followed to create a working database for this REDARS application. These steps are summarized below.

3.2.1 <u>Bridges</u>

Bridge locations must be correctly related to the highway network, in order to translate bridge damage states to system states (which show which links throughout the system are closed at various post-earthquake times). Usually, the Import Wizard develops this relationship from information provided in the National Bridge Inventory (NBI) database, through a dynamic segmentation technique. (See Section 4.5 of Cho et al., *ibid* for details.) However, because locations of many bridges were incorrectly represented in the NBI database, we could not fully utilize the Import Wizard functionality and instead had to resort to the following process.

To increase the ability to identify bridge locations and to relate them to the transportation link data, a rigorous data cleaning processes was applied. First, we obtained up-to-date bridge location data from the Caltrans Bridge Log (www.dot.ca.gov/hq/structur/strmaint/brlog2.htm), instead of using data from the NBI. Bridges that are listed multiple times in different routes were then consolidated to routes with a higher hierarchy (see Step 1 in Figure 3-3). For example, if a given bridge was listed as an interstate freeway bridge as well as a state route bridge, it was assumed to be an interstate freeway bridge. Route and mile marker data in NHPN were also corrected based on the intersection information in the bridge log file (Step 2). Then, the dynamic segmentation technique was applied to identify bridge locations on the NHPN roadway segments (Step 3). This location information was transferred to the transportation network map created from SCAG and SANDAG data, and bridges were joined to the nearest links that had an identical route ID (Step 4). Once x-y coordinates and the associated link ID were identified, all the required attributes were imported from NBI (Step 5), and ground motion data from maps provided by USGS were also integrated (Step 6).

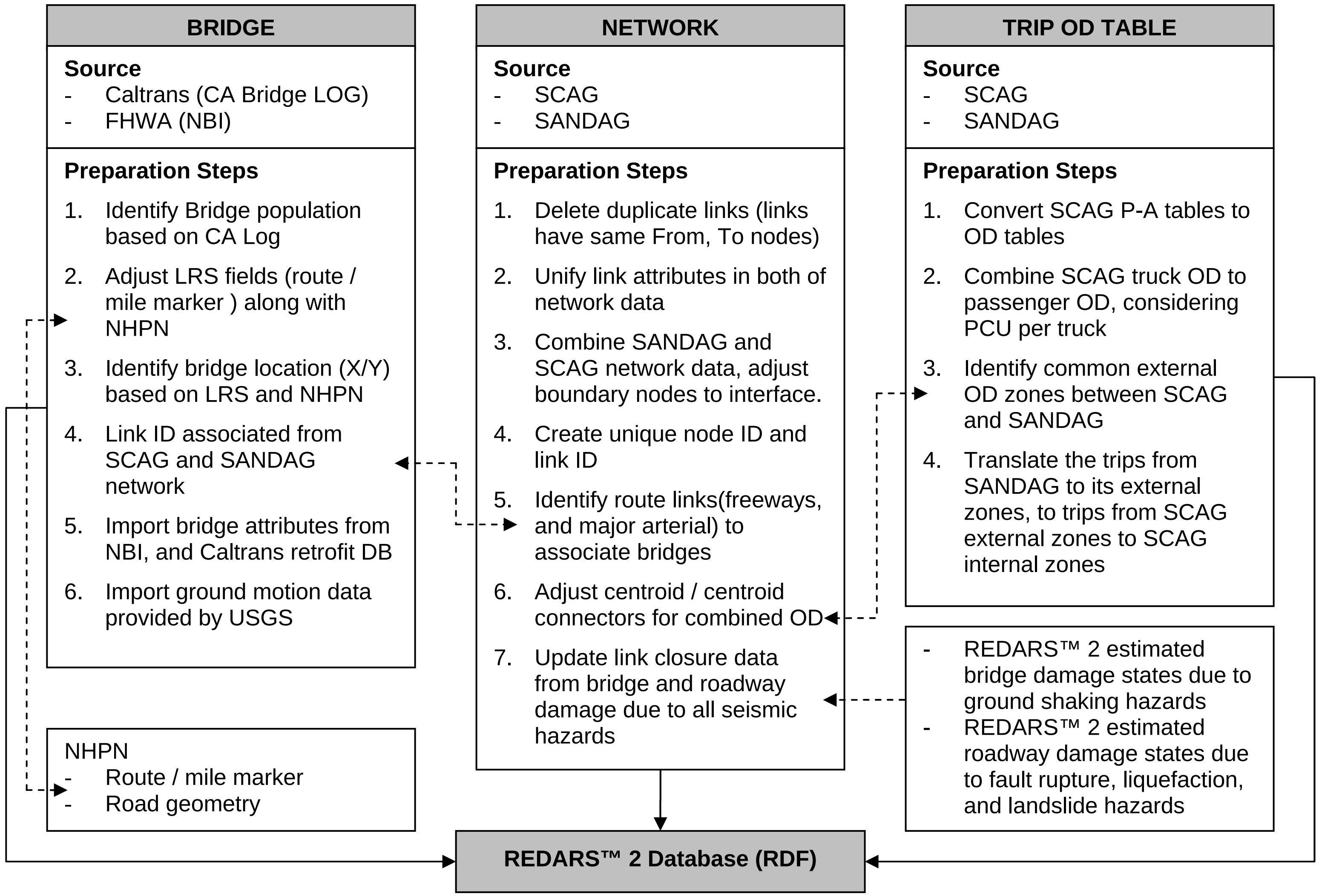
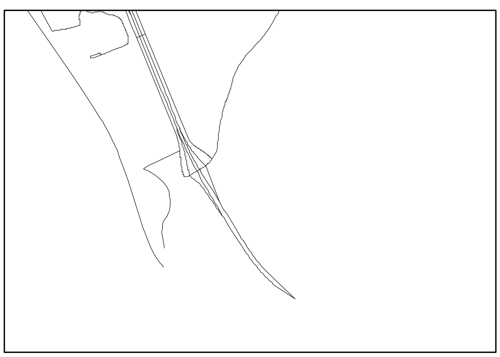


Figure 3-3 Transportation Database Development Procedure

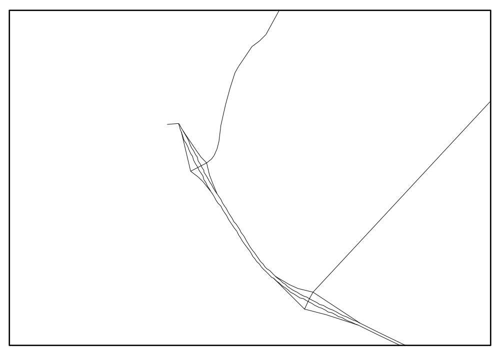
3.2.2 Network

The two sets of network data were manually *stitched* together within a GIS program to create the geometry of roadway lines, which were also readjusted for the key IDs (i.e., node ID, From-node ID, To-node ID, and global ID for links) that were set up separately by each MPO.

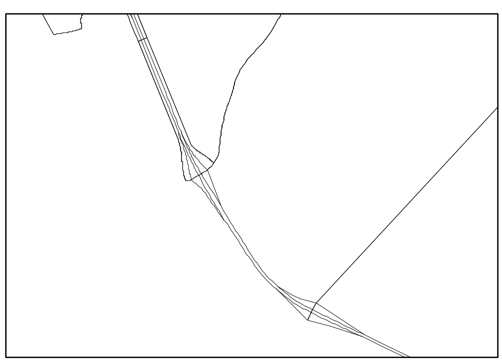
The SCAG network data was delivered a proprietary format (i.e., TransCAD map format), while the SANDAG network data was produced in ESRI SHP format. This meant that both datasets were compatible with GIS map data, instead of the stringent transportation network data, in which network connectivity is maintained by From-and-To node IDs. Some of links were duplicated with regard to the end node IDs, i.e., different geographic objects, yet same From-node ID and To-node IDs. Those duplicated links were eliminated to prevent problems in searching travel paths in the model (see Step 1 in Figure 3-3). In this step, some of dead-end links were also identified and deleted, i.e., dead-end links are not used by the model to assign trips. Before stitching the two datasets together, links attributes, such as time units of capacity per lane, free flow speed, and link types were unified (Step 2). Geographic objects, i.e., lines and points were adjusted in the stitching process to create seamless roadways crossing over the boundary of datasets (Step 3). Figure 3-4 (a) and (b) shows I-5 from SCAG data, and SANDAG data, near the Orange County and San Diego County border. After deleting dead-end links from the SCAG data, the stitched network, Figure 3-4 (c), shows a continuous I-5.



a) SCAG Network



(b) SANDAG Network



(c) Combined Network

Figure 3-4 Combined SCAG and SANDAG Networks

After the network datasets were combined into one set, unique IDs were assigned to all nodes and links (Step 4). Then, the bridges in the system were located along the appropriate links, based on the Caltrans and NHPN data summarized in Section 3.2.1 -- which was difficult and time consuming because of the very close spacing of the various highways and local roads throughout the system (Step 5). The transportation model uses special type of nodes, called centroids, and the rows and columns in the OD matrix are associated with specific centroids through its ID. As one of the ways to reduce data size, we had tried to merge rows and columns of the OD matrix in SANDAG area, as summarized in Section 3.2.3. The centroid IDs were readjusted a few times as we attempted to reduce the matrix size (Step 6).

Just before the network data was imported into REDARS™ 2 database, the ground motion, fault rupture, liquefaction, and landslide hazards data developed by USGS were incorporated and associated with the bridge, highway, and roadway components throughout the system. REDARS™ 2 then applied its damage state and repair models to these hazards in order to estimate damage states, repair costs, and downtimes for each component. These results were then used identify system-wide link closures (Step 7).

3.2.3 OD Trips

Reducing the large size of OD trip data was the most challenging step in this process. To accomplish this, we attempted several strategies. First, we reduced the data precision from double to single precision; however, the trip reduction module in the transportation model was not able to estimate the proper ratio of trip reductions for long detours. In our next attempt, we merged zones in San Diego County to about half of its original size, but the resulting matrix of 6218-by-6218 was still too large for the REDARS™ 2 database file.

The third option that we considered and eventually adopted was to: (a) include OD trip data from SCAG and exclude OD trip data from SANDAG (while retaining the SANDAG network data); and (b) merge the separate OD trip matrices from freight trips and auto trips into a single combined trip matrix. In this, we had to convert the form of the SCAG trip data, which differs from the OD trip matrix format used in REDARS™ 2, into the REDARS™ 2 trip-matrix format. This involved the following process:

- The original form of the matrices from SCAG was in a P-A (production – attraction) matrix, in which trips are counted only for the trip purposes, not for trips the drivers are actually making. For example, home-based-working trips in a P-A matrix represent the number of drivers who depart from home to the work place, and do not include return trips from work to home. Return trips are represented as a ratio of return trips to initial trip by time of day (SCAG, 2007). This differs from the OD trip matrix format used in REDARS™ 2. However, by considering these SCAG return trip ratios over different time periods, we were able to convert the SCAG P-A matrices into OD trip matrices (Step 1 in Figure 3-3).
- We merged the freight OD trips (which represents 6-percent of the total trips) to passenger OD trips (Step 2). In this, we considered that a truck contribution to traffic congestion exceeds a passenger car contribution to traffic by a factor of about 2 – 5.. To address this fact, an equivalent passenger car unit (PCU) was applied to truck trips (SCAG *ibid*).

- Trips from San Diego to Orange County or to any other SCAG area were considered to be trips from external zones (Steps 3 and 4).

3.3 EXPECTED IMPACTS OF CONGESTION IN SANDAG AREA

Figure 3-5 depicts a conceptual transportation network created for this project. Since the trips from and to SCAG area are included in the database, congestion in the shaded SCAG area would be properly modeled, both before and after the San Andreas event is introduced into the system. On the other hand, the SANDAG area includes the network, without preserving the trips within the region. The trips from SANDAG to SCAG, or SCAG to SANDAG are included as if the trips are generated and terminated at the boarder between SCAG and SANDAG. In this case, no travel cost from congestion in the SANDAG area was calculated.

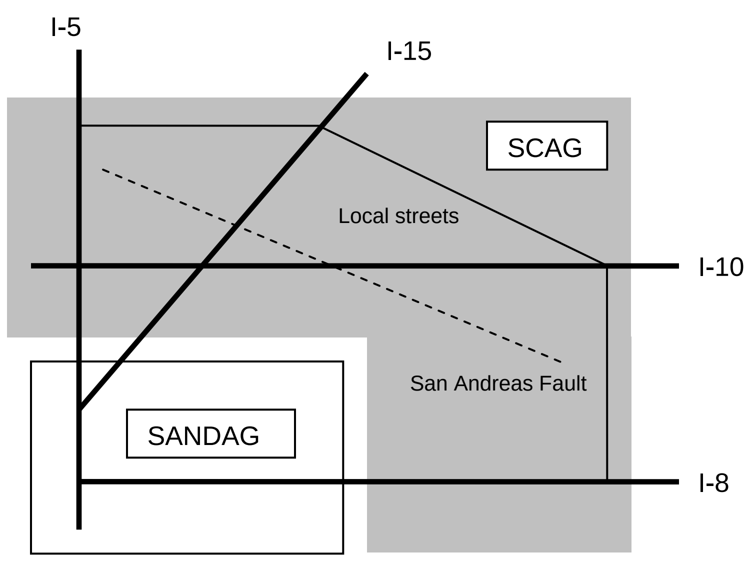


Figure 3-5 Conceptual Network Diagram

The economic loss calculation in REDARS™ 2 is based on the travel time differences throughout the highway-roadway network before and after the earthquake, and will depend on the network's traffic-carrying capacity at various post-earthquake times. In this analysis, there would be no damage to bridges in the SANDAG area from the San Andreas event. And, there would be no change in the capacity of this area. Therefore, no damage to San Diego County would be expected in this scenario. The inclusion of SANDAG network, however, will contribute to the losses in that trips resulting from detours caused by the closure of the I-10 or I-15 to I-8 and I-5 will be included.

CHAPTER 4
ANALYSIS RESULTS

This chapter describes the results from our analyses of the seismic risks to the Southern California highway system due to the scenario earthquake being considered in this Golden Guardian (GG) exercise. The chapter is organized into three main sections. First, Section 4.1 summarizes the seismic hazards that have been estimated by USGS under this exercise. Then, Section 4.2 describes our estimates of component damage states, repair requirements, and system states due to these seismic hazards. Finally, Section 4.3 provides the results of our analyses of the post-earthquake traffic flows, travel times, trip demands throughout the highway system, and the losses due to region-wide travel and traffic disruptions.

4.1 SEISMIC HAZARDS

4.1.1 Scenario Earthquake

The scenario earthquake considered in this project has a moment magnitude of 7.8 and is generated by rupture of a 300-km long segment of the southern San Andreas Fault that extends from Bombay Beach along the Salton Sea in Imperial County up through the Lake Hughes area in the Traverse Range north of Los Angeles. Figure 4-1 shows the proximity of this fault rupture to the major roadways in the Southern California highway system (Ponti, 2007).

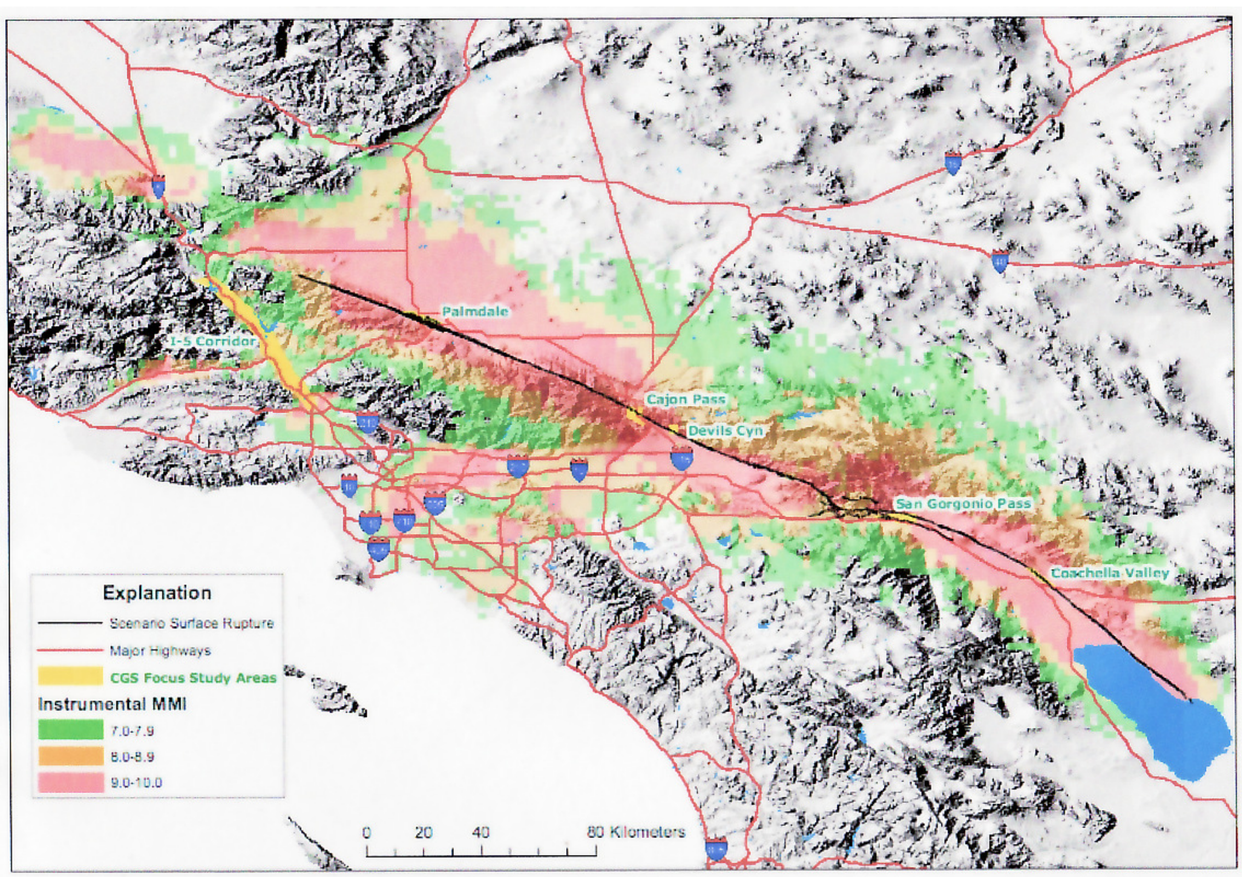


Figure 4-1. Proximity of Earthquake Fault Rupture to Major Highways (Ponti, 2007)

4.1.2 Ground Motions

As noted in Chapter 2, USGS estimates of region-wide ground motions have been provided as ShakeMap-type shapefiles that were imported into REDARS™ 2 for use in this analysis. Figure 4-2 provides a map of these ground motions, in terms of spectral accelerations at a natural period of 1.0 sec. which, as described in Chapter 2, is the parameter used by the REDARS™ 2 default bridge model to estimate damage states for most of the bridges in the region.

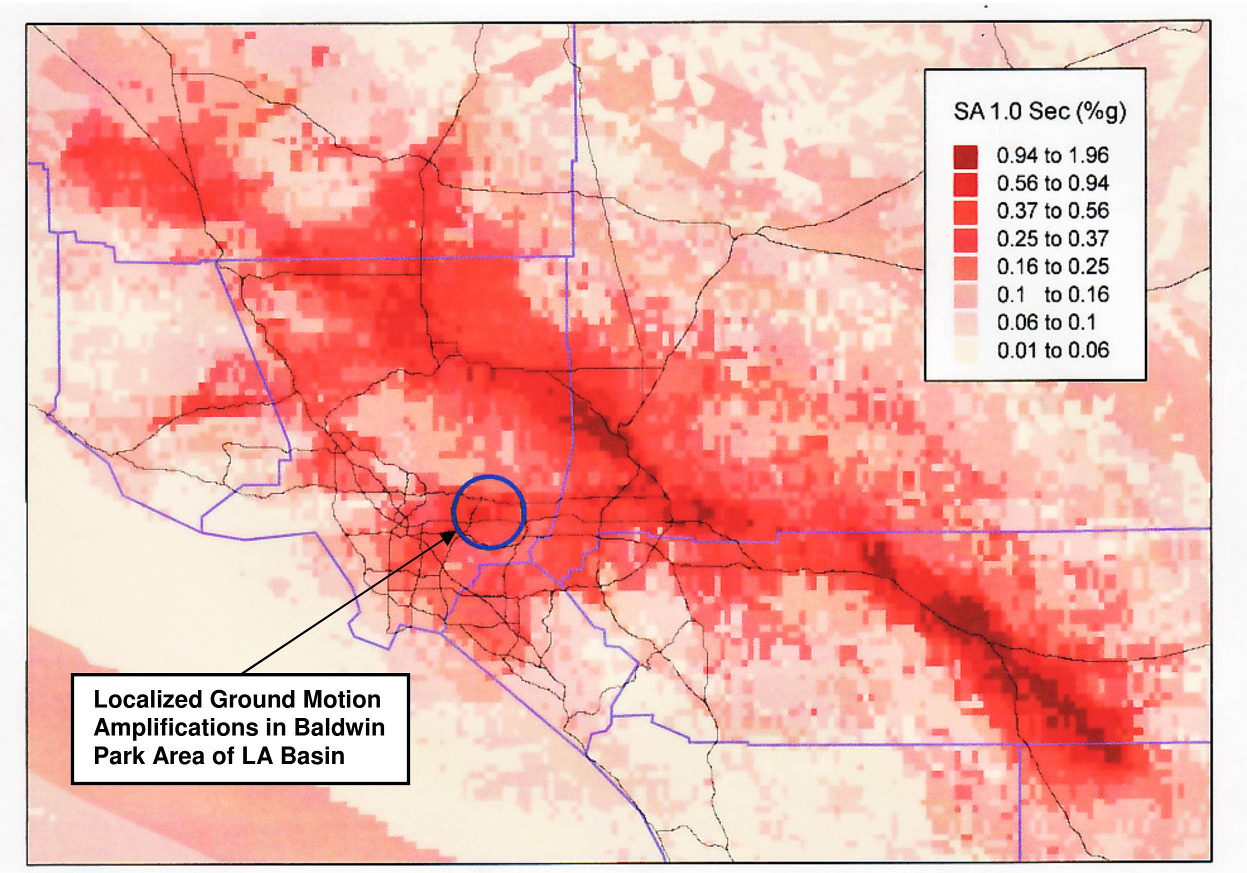


Figure 4-2. ShakeMap Representation of Spectral Accelerations at Natural Period = 1.0 sec due to GG Exercise Scenario Earthquake

Figure 4-2 shows that the spectral accelerations in the vicinity of the fault rupture are very high, reaching values in the 0.94 g to 1.96 g range along the southern part of the rupture and also in the San Bernadino and Cajon Pass areas. These motions generally attenuate fairly rapidly with increasing distance from the fault rupture. However, some localized amplifications of the ground motions are observed in the Baldwin Park and Monterey Park within the eastern portion of the greater Los Angeles area (see blue circled area in Figure 4-2). The impacts of these ground motions throughout the study area on the seismic performance of the bridges in this area are discussed later in this chapter.

4.1.3 Surface Fault Rupture

USGS has provided us with tabulations of permanent ground displacement (PGDs) due to surface-fault-rupture at roadway locations within the highway-roadway system that are crossed by the ruptured segments of the Southern San Andreas Fault. These PGDs at the corresponding links within our highway system model were then manually input into REDARS™ 2. They are primarily strike-slip (horizontal) with generally small vertical components (Ponti, 2007). All of the fault crossings identified by USGS were at roadways; i.e., none of the crossings were at bridge locations. Table 4-1 shows ranges of PGDs at roadway locations within the project study area that USGS provided to us for input into the REDARS™ 2 analysis (Ponti, 2007).

Table 4-1. Surface Fault Displacements at Roadway Locations in Study Area

Locations shown in Figure 4-1	Ground Displacements along Roadways in Fault Rupture Area, meters
Coachella Valley Focus Area	4.0 – 7.2
San Gorgonio Pass Area	2.0 – 6.7
Cajon Pass	0.7 – 1.1
Palmdale Focus Area	0.3 – 3.0

4.1.4 Liquefaction

The California Geologic Survey (CGS) has estimated liquefaction hazards in focus areas located in the Coachella Valley, Cajon Pass, San Gorgonio Pass, and Palmdale areas (Real et al., 2007). Their estimates show the presence of liquefaction hazards at various roadway locations in the Coachella Valley and San Gorgonio Pass areas only. PGDs estimated by CGS at these roadway locations (Table 4-2) were assigned to corresponding links in the REDARS™ 2 highway system model and were then manually input into REDARS™ 2. All of the liquefied roadway locations identified by CGS were along highway pavements; i.e., none of the liquefaction hazards were located at bridges. .

Table 4-2. Liquefaction-Induced PGDs at Roadway Locations (Real et al., 2007)

Locations shown in Figure 4-1	Liquefaction-Induced Ground Displacements along Roadways, meters
Coachella Valley Focus Area	4.0 – 7.2
San Gorgonio Pass Focus Area	3.0 – 7.0
Cajon Pass Focus Area	none
Palmdale Focus Area	none

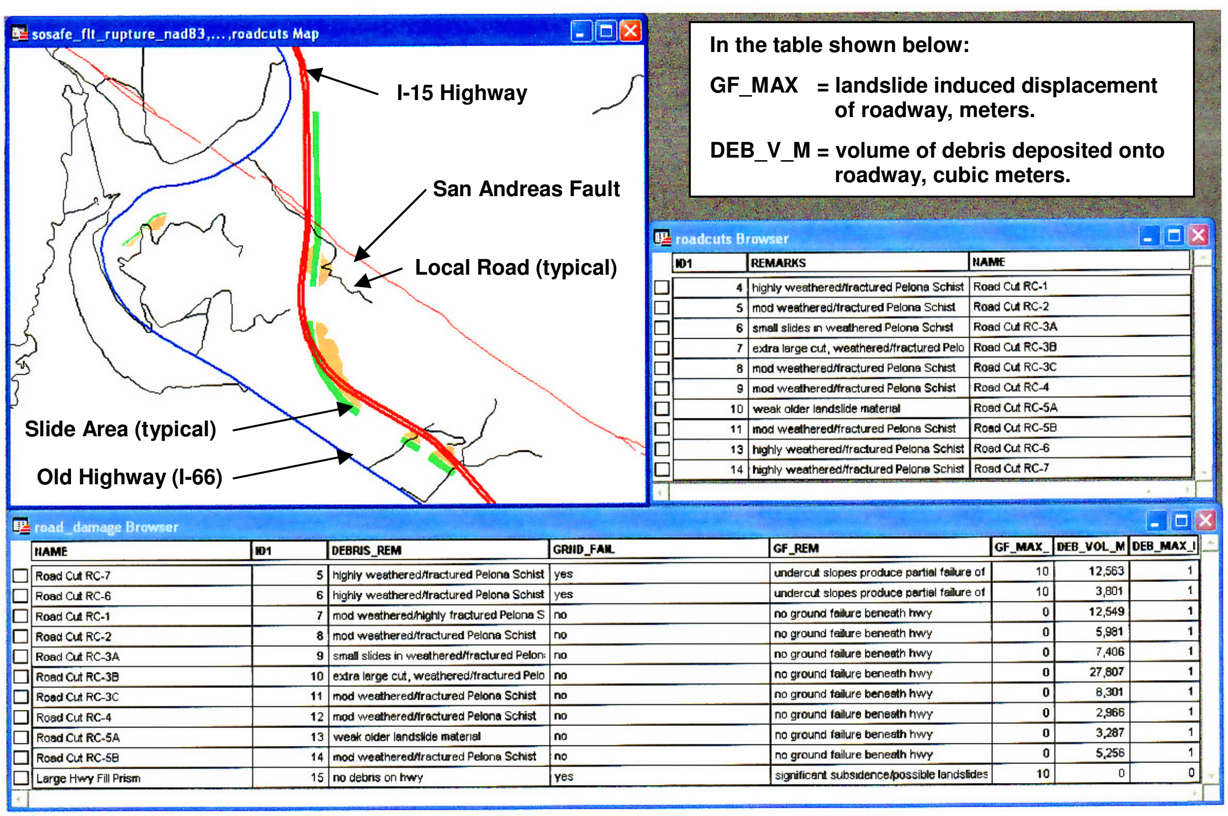
4.1.5 Landslide

As part of this GG exercise, the CGS also assessed potential earthquake-induced landslide hazards to the highway system along the Cajon Pass and San Gorgonio Pass (Wilson et al., 2007). Such hazards can impact post-earthquake traffic flows by causing PGDs that damage the roadway or by depositing debris onto the roadway that blocks traffic and must be removed in order to restore normal traffic flows. These hazards within the Cajon Pass and San Gorgonio Pass, were provided as shapefiles that were read by REDARS™ 2.

As noted in Chapter 1, no data for other earthquake-induced landslide hazards were available at the time of this REDARS™ 2 analysis. Therefore, the only landslide hazards included in this analysis were those at the Cajon and San Gorgonio Passes as estimated by CGS.

4.1.5.1 Cajon Pass

Figure 4-3 summarizes the geologic conditions along the slopes within the Cajon Pass, along with estimated landslide-induced PGDs and debris volumes along the roadways. According to this figure, potential slides are predicted at 10 road cut locations within the Pass. PGDs of 10 m. are estimated at three of these locations (at the highway fill prism along I-15 and at Road Cuts 6 and 7 that undercut the Old Highway (I-66)). The CGS analysis indicates that all of the road cut areas listed in Figure 4-3 will deposit debris along I-15 and the Old Highway.



ID1	REMARKS	NAME
4	highly weathered/fractured Pelona Schist	Road Cut RC-1
5	mod weathered/fractured Pelona Schist	Road Cut RC-2
6	small slides in weathered Pelona Schist	Road Cut RC-3A
7	extra large cut, weathered/fractured Pelo	Road Cut RC-3B
8	mod weathered/fractured Pelona Schist	Road Cut RC-3C
9	mod weathered/fractured Pelona Schist	Road Cut RC-4
10	weak older landslide material	Road Cut RC-5A
11	mod weathered/fractured Pelona Schist	Road Cut RC-5B
13	highly weathered/fractured Pelona Schist	Road Cut RC-6
14	highly weathered/fractured Pelona Schist	Road Cut RC-7

NAME	ID1	DEBRIS_REM	GRND_FAIL	GF_REM	GF_MAX_	DEB_VOL_M	DEB_MAX_I
Road Cut RC-7	5	highly weathered/fractured Pelona Schist	yes	undercut slopes produce partial failure of	10	12,563	1
Road Cut RC-6	6	highly weathered/fractured Pelona Schist	yes	undercut slopes produce partial failure of	10	3,801	1
Road Cut RC-1	7	mod weathered/highly fractured Pelona S	no	no ground failure beneath hwy	0	12,549	1
Road Cut RC-2	8	mod weathered/fractured Pelona Schist	no	no ground failure beneath hwy	0	5,981	1
Road Cut RC-3A	9	small slides in weathered/fractured Pelon:	no	no ground failure beneath hwy	0	7,406	1
Road Cut RC-3B	10	extra large cut, weathered/fractured Pelo	no	no ground failure beneath hwy	0	27,807	1
Road Cut RC-3C	11	mod weathered/fractured Pelona Schist	no	no ground failure beneath hwy	0	8,301	1
Road Cut RC-4	12	mod weathered/fractured Pelona Schist	no	no ground failure beneath hwy	0	2,966	1
Road Cut RC-5A	13	weak older landslide material	no	no ground failure beneath hwy	0	3,287	1
Road Cut RC-5B	14	mod weathered/fractured Pelona Schist	no	no ground failure beneath hwy	0	5,256	1
Large Hwy Fill Prism	15	no debris on hwy	yes	significant subsidence/possible landslides	10	0	0

Figure 4-4. Earthquake-Induced Landslide Hazards at Cajon Pass (Wilson et al., 2007)

4.1.5.2 San Gorgonio Pass

The CGS report identifies two landslide scenarios at the San Gorgonio Pass: (a) a moderate slide that would deposit at least 60,000 yd3 of material onto the I-10 highway; or (b) a catastrophic failure of the hillside, which CGS considers to be an unlikely but possible scenario that could deposit up to 2 million cubic yards of debris onto the roadway. Our REDARS™ 2 analysis has considered the first scenario, since it is viewed to be more likely by CGS.

4.2 COMPONENT DAMAGE STATES

4.2.1 Bridges Damage due to Ground Shaking

This section summarizes REDARS™ 2 estimates of bridge damage due to the ground motion hazards summarized in Section 4.1.1. Because no bridges were sited at locations of fault rupture, liquefaction, and landslide hazards along the region's roadways that were identified by USGS, no estimates of bridge damage due to PGD were needed under this project.

4.2.1.1 Bridges in Study Area

. The Southern California highway system area contains 6,719 bridges whose locations are shown in Figure 4-5. Of these bridges, 1,611 have undergone a Phase 2 retrofit (Yashinsky, 2005), which has most commonly consisted of jacketing of the bridge columns. In view of this, and because no data were available regarding other types of Phase 2 retrofits that may have been carried out at some of the 1,611 retrofitted bridges, we have assumed that structural-capacity enhancements due to Phase 2 retrofits can be represented by the enhancements due to column jacketing that are included in the REDARS™ 2 (see Chapter 2).

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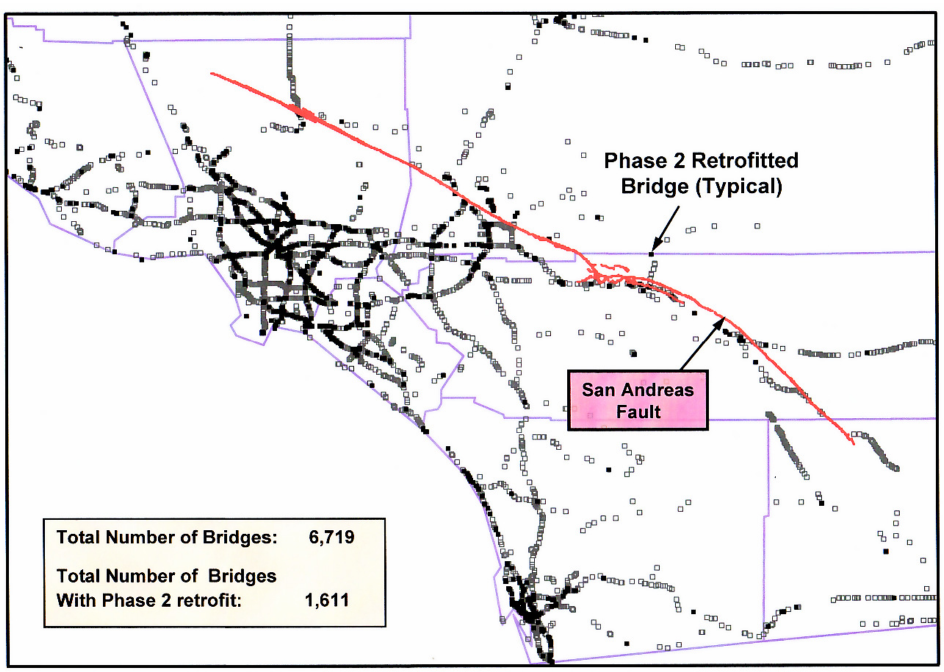


Figure 4-5. Bridges in Study Area

4.2.1.2 Damage Results

These analysis results show that the principal bridge damage occurs within the five zones shown in Figure 4-6. These zones are located near Indio (Zone 1), Palm Springs (Zone 2), San Bernadino (Zone 3), Palmdale (Zone 4), and Baldwin Park (Zone 5). Four of these zones (Zones 1-4) are located very near the ruptured segment of the San Andreas Fault where, as shown in Figure 4-2, the ground motions are very severe. Zone 5 is located at a location away from the fault rupture but in an area where localized amplifications of ground shaking have been predicted (see blue circled area in Figure 4-2).

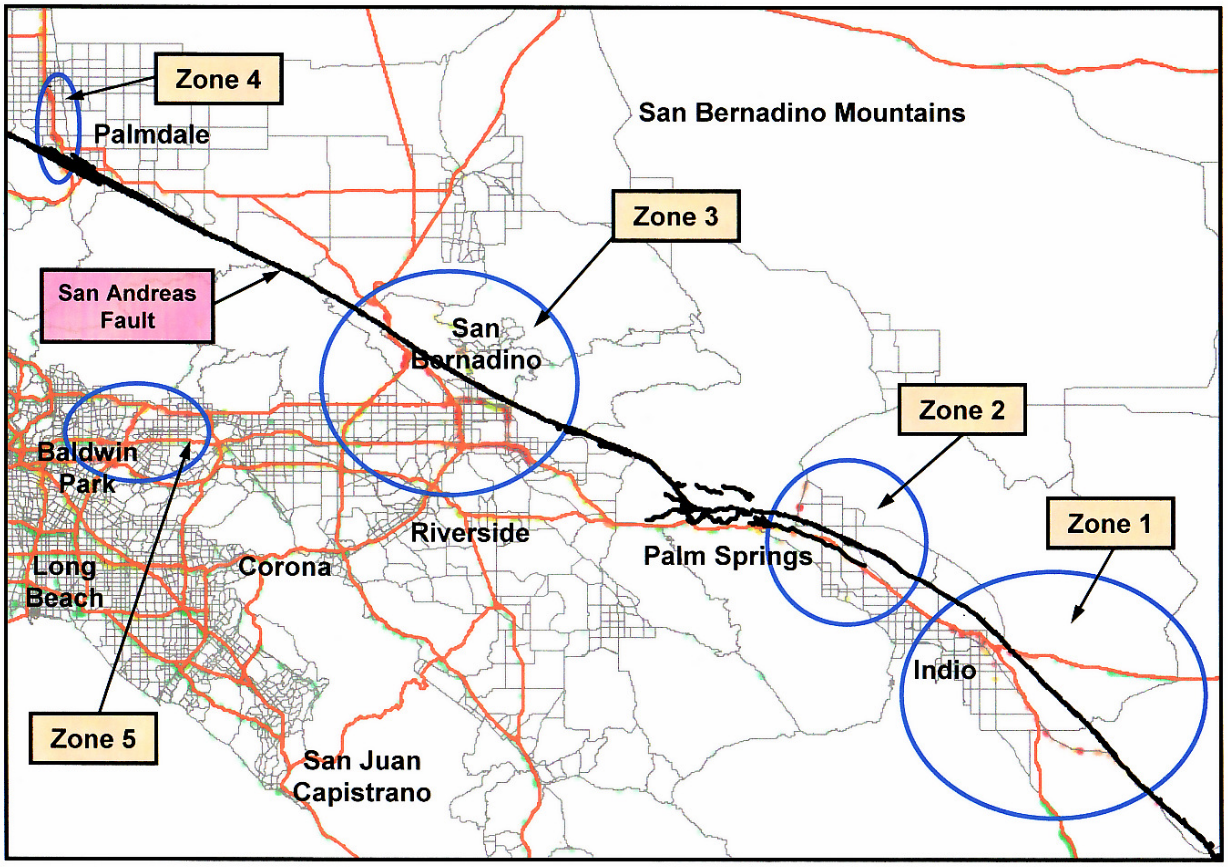
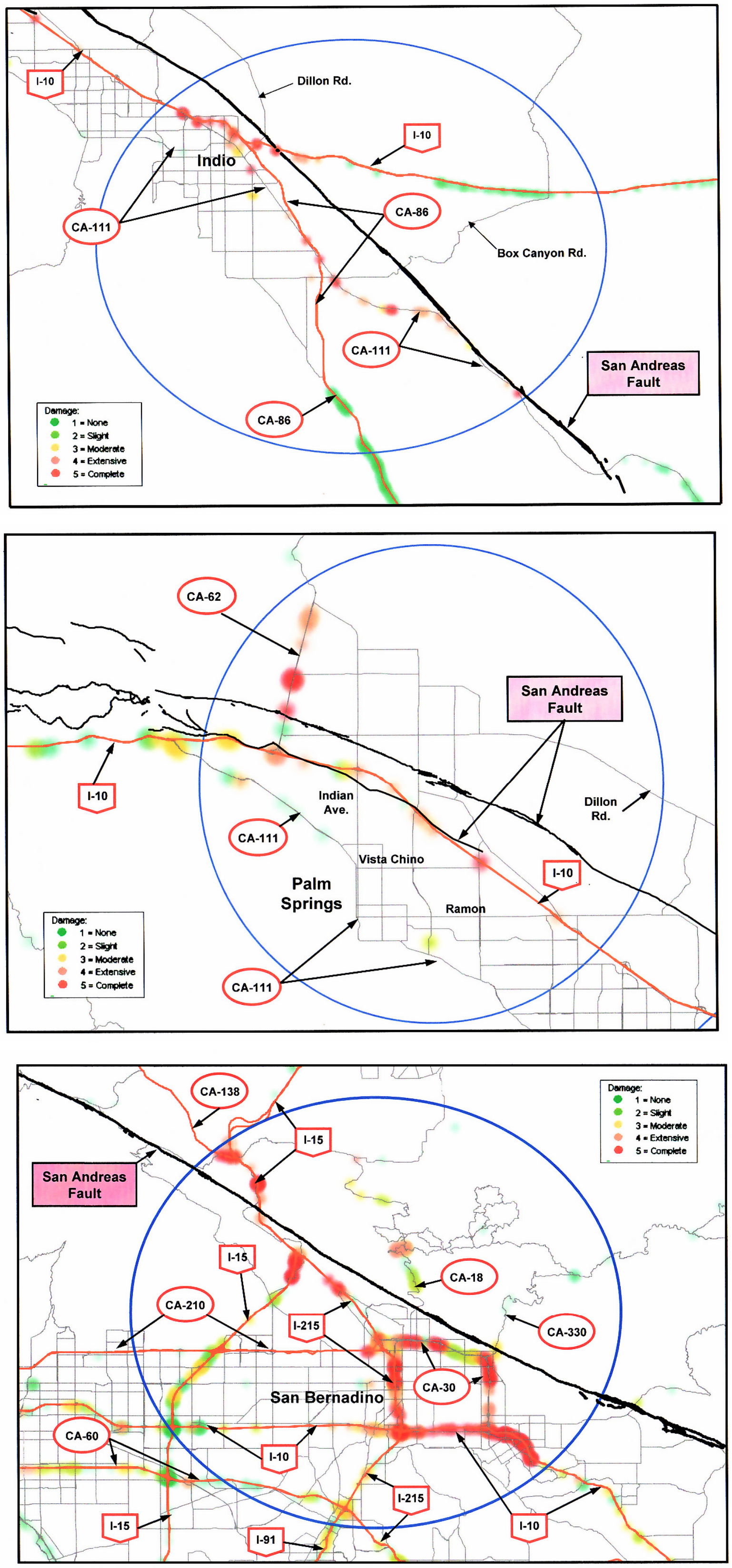


Figure 4-6. Locations of Most Severe Bridge and Roadway Damage

Figures 4-7a through 4-7e provide additional information on the bridge damage within Zones 1 through 5 that is summarized as follows:

- Each zone contains at least some highway bridges with so-called “complete” damage (hereafter termed irreparable damage) that requires rebuilding of the bridge. The default bridge repair model shown in Table 2-4 indicates that, under non-emergency repair conditions, the bridge will be closed to traffic for about 5-7 months, depending on the number of spans in the bridge.
- The most widespread damage is in the San Bernadino area (Zone 3) which, of all the zones shown in Figure 4-6, contains the largest number of bridges.

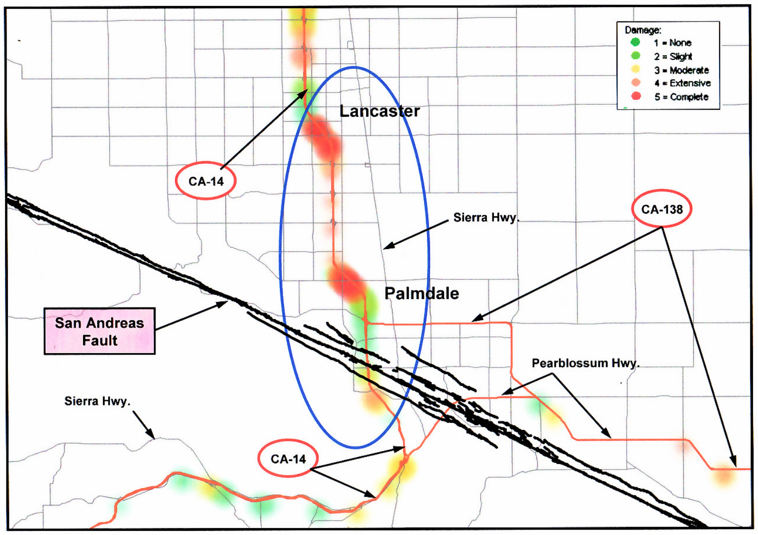


a) Zone 1 (Indio and Vicinity)

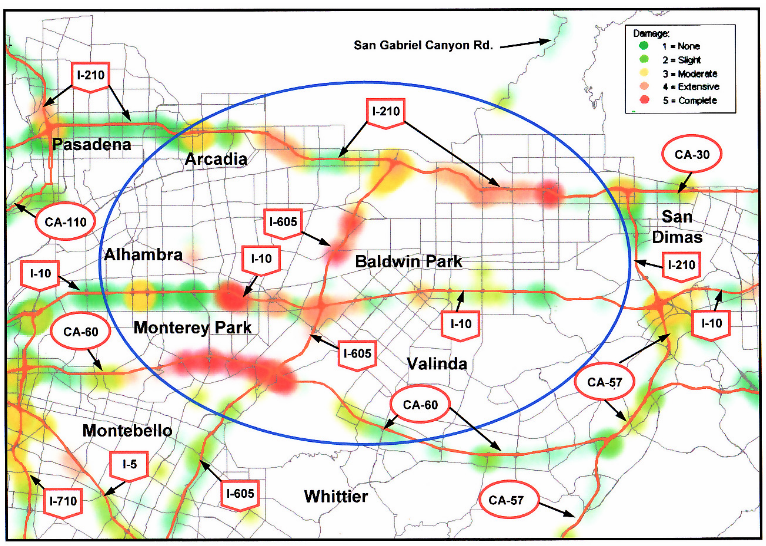
b) Zone 2 (Palm Springs and Vicinity)

c) Zone 3 (San Bernadino and Vicinity)

Figure 4-7. Locations of Most Severely Damaged Bridges (Part 1 of 2)



d) Zone 4 (Palmdale and Vicinity)



e) Zone 5 (Baldwin Park and Vicinity)

Figure 4-7. Locations of Most Severely Damaged Bridges (Part 2 of 2)

- About 90-percent of the bridges with irreparable damage correspond to older bridges (constructed before 1975) that, according to the Caltrans bridge data provided by Yashinsky (2005), have not undergone a Phase 2 retrofit. The REDARS™ 2 default bridge model described in Chapter 2 estimates a reduced structural capacity for such bridges, because they were presumably designed before Caltrans' seismic design procedures were substantially upgraded after the 1971 San Fernando Earthquake. Thus, such older bridges, and particularly bridges of this vintage that have not undergone a Phase 2 retrofit, are considered to be much more vulnerable than bridges designed during or after 1975 or bridges with a Phase 2 retrofit.
- This examination of the bridge-attribute data shows that bridges designed during or after 1975 or older bridges with a Phase 2 retrofit performed relatively well. In fact, only slightly more than 10-percent of the bridges with irreparable damage were in this category, and virtually all of these bridges were subjected to very severe ground shaking (with spectral accelerations at a period of 1.0 sec. that averaged 1.32 g and ranged from 1.07 g to 1.81 g).

- Finally, it is important to recognize that the estimated ground motions due to this scenario earthquake are very strong, particularly in the vicinity of the fault rupture where most of the very severe bridge damage is located. In fact, the overall intensities of these ground motions exceed anything that has been recorded during recent major earthquakes world wide. This is undoubtedly an important reason for the extent of the bridge damage that has been predicted (e.g., see Table 4-6)

Table 4-6. Intensity of Ground Motions at Sites of Bridges with "Complete" Damage State

Zone	Ground Motion (Spectral Acceleration at Natural Period = 1.0 sec.), g	
	Average	Range
1. Indio and Vicinity	1.38	0.97 – 1.96
2. Palm Springs and Vicinity	1.18	0.85 – 1.41
3. San Bernadino and Vicinity	0.89	0.63 – 1.81
4. Palmdale and Vicinity	0.66	0.65 – 0.66
5. Baldwin Park and Vicinity	0.59	0.37 – 0.73

4.2.1.3 Discussion of Results

When interpreting the above bridge-damage results, the following bridge modeling and input data considerations should be kept in mind (see Sec. 5.2) for further discussion.).

- ***Bridge Model.*** The REDARAS™ 2 default bridge model that is summarized in Chapter 2 was developed for rapid analysis of the large number of bridges within a highway system. Therefore, it is, by necessity, a simplified model. Furthermore, it is based primarily on the limited bridge-specific structural attribute data that is contained in the FHWA NBI database, (as discussed in Section 2.3.2.2.1). Therefore, this model is not intended to replace a more detailed model that considers the full range of bridge-specific structural attributes that are relevant to seismic response. Rather, it should be viewed as a screening tool for assessing system-wide bridge damage patterns throughout the highway system. Where appropriate, the damage estimates from this simplified model should be checked by more detailed analysis.

- ***Input Data.*** Bridge attribute data contained in the NBI database and also in the Caltrans database provided by Yashinsky (2005) indicate that: (a) many bridges in the near-fault region have been designed prior to the mid-1970s using the limited seismic design procedures that were in place at that time; and (b) many of these bridges had not undergone a Phase 2 retrofit. Since most of the irreparable damage is estimated to occur at such bridges, these data should be carefully checked. If it turns out that many of these older bridges have indeed undergone a Phase 2 retrofit or some other type of seismic upgrade that improves seismic performance, the extent of the damage to these bridges could be reduced relative to the damage estimates from this analysis.

4.2.2 Highway Damage due to Permanent Ground Displacements

4.2.2.1 Damage Results

As noted earlier in this chapter, locations of PGDs along the entire extent of the highway system due to surface fault rupture, liquefaction, and landslide hazards have been provided to us in shapefile or tabulated form, and have been imported into REDARS™ 2 for use as input into the highway system SRA.

The REDARS™ 2 default model for highway pavements subjected to PGD that is provided in Table 4-7 indicates that, under non-emergency repair conditions, PGDs in excess of 12 in. will require removal and replacement of the existing pavement and subsurface materials. According to this model, this will require full closure of the roadway for seven weeks while these removal/replacement operations are being carried out.

Tables 4-1 and 4-2 and Figure 4-4 all show PGDs due to fault rupture, liquefaction, and landslide hazards from this scenario earthquake that far exceed the above 12 in. displacement level that would trigger roadway replacement according to our repair model. This has serious consequences, particularly the PGDs due to fault rupture which extend over the entire 300 km length of the fault rupture for this scenario earthquake. For example, this would result in seven weeks of full shutdown of I-10, which is a major transportation corridor into and out of the greater Los Angeles area for westbound and eastbound traffic. In addition, travel along I-15 which is major transportation corridor for northbound and southbound traffic for populated areas in the eastern segments of Los Angeles and Orange Counties will be similarly shut down. Closures of the other interstate, state, and local roadways crossed by the fault rupture would have additional local impacts.

Similarly large displacements due to liquefaction and landslide hazards would have similar impacts where they occur along interstate, state, and local highways and roadways throughout the study area. However, since these hazards are more localized than the fault-rupture hazards, their overall impact on the study area's highway-roadway transportation system will likewise be relatively localized.

4.2.2.2 Discussion of Results

When evaluating these results, the following considerations should be kept in mind:

- If a major freeway/interstate-highway such as I-10 or I-15 were severely damaged, it is probable that every effort would be made to accelerate the repairs of these highways and shorten their down time. If sufficient resources are available, repairs of these highways could be expedited through a bonus-incentive repair program that was successful in substantially shortening downtimes of bridges that had to be replaced after the 1994 Northridge Earthquake and also after the 2007 MacArthur Maze fire in the San Francisco Bay Area.
- However, what might offset this is the possibility that, as noted earlier in this report, this very large scenario earthquake could lead to widespread damage not only to the highway system but also to other elements of the region's built infrastructure. This could result in

competition for scarce repair resources that, in turn, could slow repair operations until additional repair resources from other parts of the state and the nation could be transported to this earthquake-stricken region. Of course, this underscores the importance of pre-earthquake emergency response planning damage-repair planning of how to establish and maintain sufficient repair resources that could be quickly mobilized after a major earthquake.

- It may be appropriate to re-examine the displacement limits that trigger roadway replacement in the current REDARS™ 2 repair model. For example, the model does not differentiate between the direction of the PGDs; i.e., whether they are horizontal or vertical. It would seem that, if earthquake-induced PGDs greater than 12-in. occur that are primarily horizontal, temporary repairs that would reopen the roadway to at least partial traffic could be implemented more rapidly than if the PGDs were primarily vertical. This should be further discussed with Caltrans roadway construction/maintenance staff members.

4.2.3 <u>Highway Blockage due to Landslide-Induced Debris</u>

As noted in Chapter 2, Caltrans staff have recommended the following approach for estimating rates of removal of debris from landslides in the Cajon Pass and San Gorgonio pass: (a) sufficient repair resources can be rapidly mobilized at the landslide sites; and (c) on this basis, about 5,000 yd^3/day of debris can be removed if the slide area can be accessed by trucks from one side only, and that about 10,000 yd^3/day of debris can be removed if the slide area can be accessed by trucks from both sides of the slide. Using these assumptions, debris removal times at the Cajon Pass and San Gorgonio Pass landslides were estimated as described below.

4.2.3.1 Cajon Pass Landslide

Figure 4-8 (extracted from the CGS report) shows the locations of the slides estimated by CGS for the Cajon Pass area, and Table 4-7 shows the estimated volumes of debris from each slide. This figure shows a series of several slides along a mountainous section of I-15 within which there are no intersecting roadways that could provide truck access to interior slides within this series. Thus, it appears that trucks would need to initially access the slide area separately from the north (to begin removing debris from RC-1 and RC-2a) and from the south (to begin removing debris from RC-5A and RC-5B). Then, these simultaneous debris-removal operations would work their way in toward the interior of the slide area to remove the debris from the interior slides. On this basis, and assuming a debris-removal rate of 5,000 yd^3/day for truck access from one slide of the slide only and 10,000 yd^3/day for access from both sides of the slide, the estimated debris-removal operations along I-15 would proceed as shown in Table 4-7 and summarized below:

- Working from the north, the debris from RC-1, RC-2, and RC-3 (total volume = 33,924 yd^3) would be removed within about 7 days after the start of operations. Also, simultaneously working from the south, the removal of debris from RC-5B, RC-5A, RC-4, and RC-3C (total volume = 26,612 yd^3) would be completed within about 5 days after the start of operations.

- During Day 6, the operations from the south would begin to remove the relatively large volume of debris from RC-3B (volume = 36,372 yd^3). After two days (by the end of Day 7), about 10,000 yd^3 of debris would be removed from this RC, leaving a remaining debris volume of 26,372 yd^3).

- At the start of Day 8, when the operations from the north would first reach RC-3B, removal of the debris from that RC would proceed simultaneously from the north and south. Assuming a debris-removal rate of about 10,000 yd^3/day, an estimated 3 additional days (through Days 8-10) would be needed to complete debris removal from RC-3B.
- Thus, it is estimated that about 10 days from the start of debris-removal operations would be needed to remove all of the debris along I-15 from the landslides in the Cajon Pass.

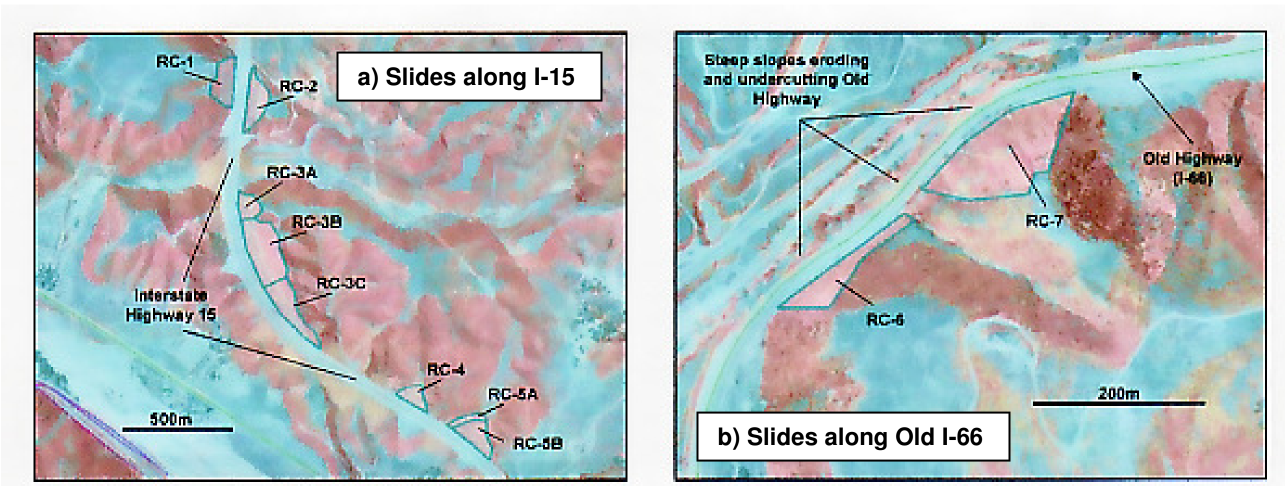


Figure 4-8. Earthquake-Induced Landslide Locations at Cajon Pass (Wilson et al., 2007)

Table 4-7. Landslide Debris Volumes

Highway	Location	Slide Debris Volumes		Debris Removal Estimates	
		Cubic meters	Cubic yards	Location(s) of Debris Removal Operations	Time Sequence of Debris Removal Operations
I-15	RC-1	12,549	16,414	From the north only	Days 1-7
	RC-2	5,981	7,823	↓	↓
	RC-3A	7,406	9,687		
	RC-3B	27,807	36,372	From the south and the north	Days 8-10
				From the south	Days 6-7
	RC-3C	8,301	10,858	↑	↑
	RC-4	2,966	3,880		
	RC-5A	3,287	4,299		
	RC-5B	5,256	6,875	From the south only	Days 1-5
Old I-66	RC-6	3,801	4,971	From the south only	Days 1-2
	RC-7	12,563	16,550	From the north only	

Along Old I-66, it is assumed that the slide along RC-6 would be accessed by trucking from the south, and that the slide along RC-7 would be accessed by trucking from the north. Since these slides are relatively close together, it is reasonable to assume that the debris from both slides (total volume = 21,521 yd^3) would be removed by trucking from both access locations at a rate of 10,000 yd^3/day. From this, it is estimated that the debris along Old I-66 can be removed within about 2 days. However, the CGS report indicates that undercut slopes at these locations could cause partial failure of the Old I-66 highway. Repair of the roadway from these failures will probably take much longer than the estimated time of 2 days to remove landslide debris.

4.2.3.2 San Gorgonio Pass Landslide

CGS has estimated that the most likely landslide scenario for the San Gorgonio Pass will deposit 60,000 yd^3 of debris onto I-10 (Sec. 4.1.4.2). Assuming truck access from both sides of this slide, the estimated time to remove this debris is 60,000 yd^3/(10,000 yd^3/day) = 6 days.

4.3 POST-EARTHQUAKE SYSTEM STATES

This section describes region-wide system states developed by applying the default repair models described in Section 2.3.2.2 to the bridge and highway pavement damage states due to the ground shaking, fault rupture, liquefaction, and landslide hazards that have been described in Section 4.2. These system states were developed at the following five different post-earthquake times that represent various repair completion milestones from the REDARS™ 2 repair model.

- ***0-3 Days after Earthquake (Fig.4-9)*** This system state represents the roadway closures immediately after the earthquake, and before repairs to any of the damage to the bridges and highways have been initiated. It shows extensive roadway closures in the vicinity of the fault rupture all along the 200 mile length of the rupture, and also at various locations within the Los Angeles basin (particularly to the north and east of the Basin.).

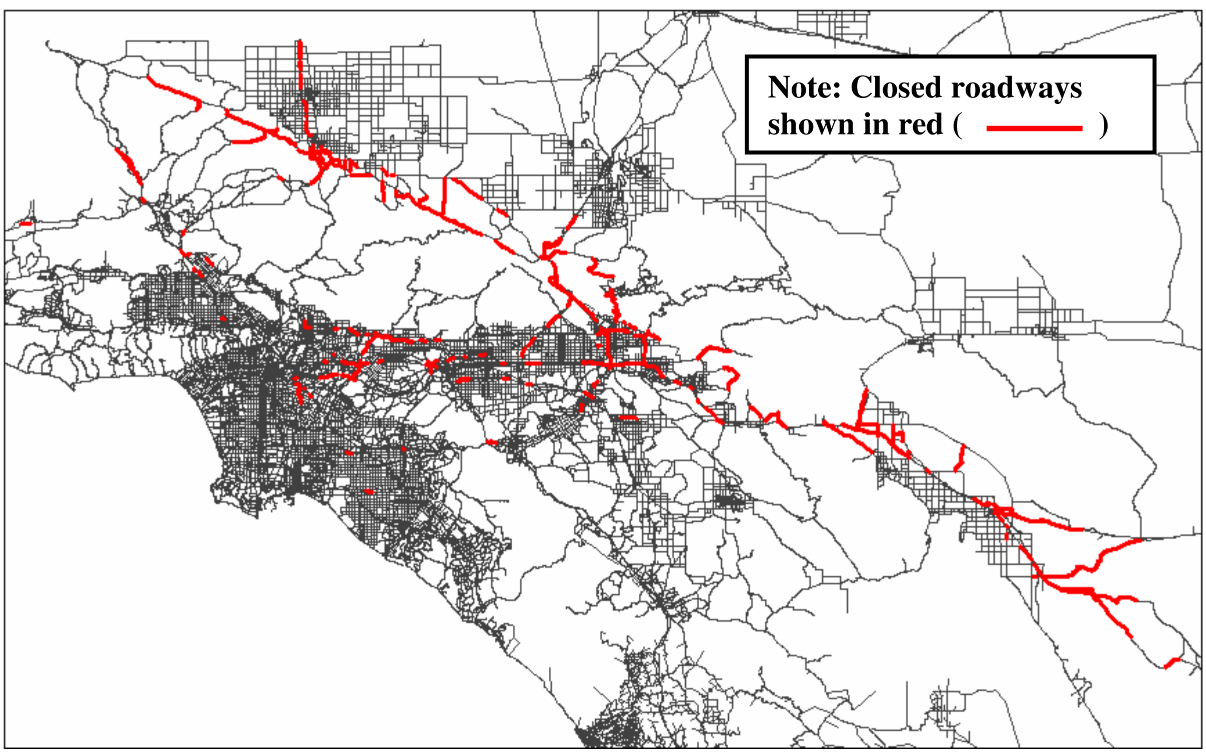


Figure 4-9. Roadway Closures at 3 Days after Earthquake (Prior to Initiation of any Damage Repair)

- ***12 Days after Earthquake (Fig.4-10).*** At this post-earthquake time, all moderately damaged bridges and moderately and extensively damaged roadways have been reopened to traffic. The closures that remain are due to extensively damaged and irreparably damaged bridges and to irreparably damaged roadways. Comparison of Figures 4-9 and 4-10 shows that most of the reopened roads are in Los Angeles and Kern Counties. Major closures remain along the fault rupture and, to a lesser extent, in the Los Angeles basin and along I-5 to the north.

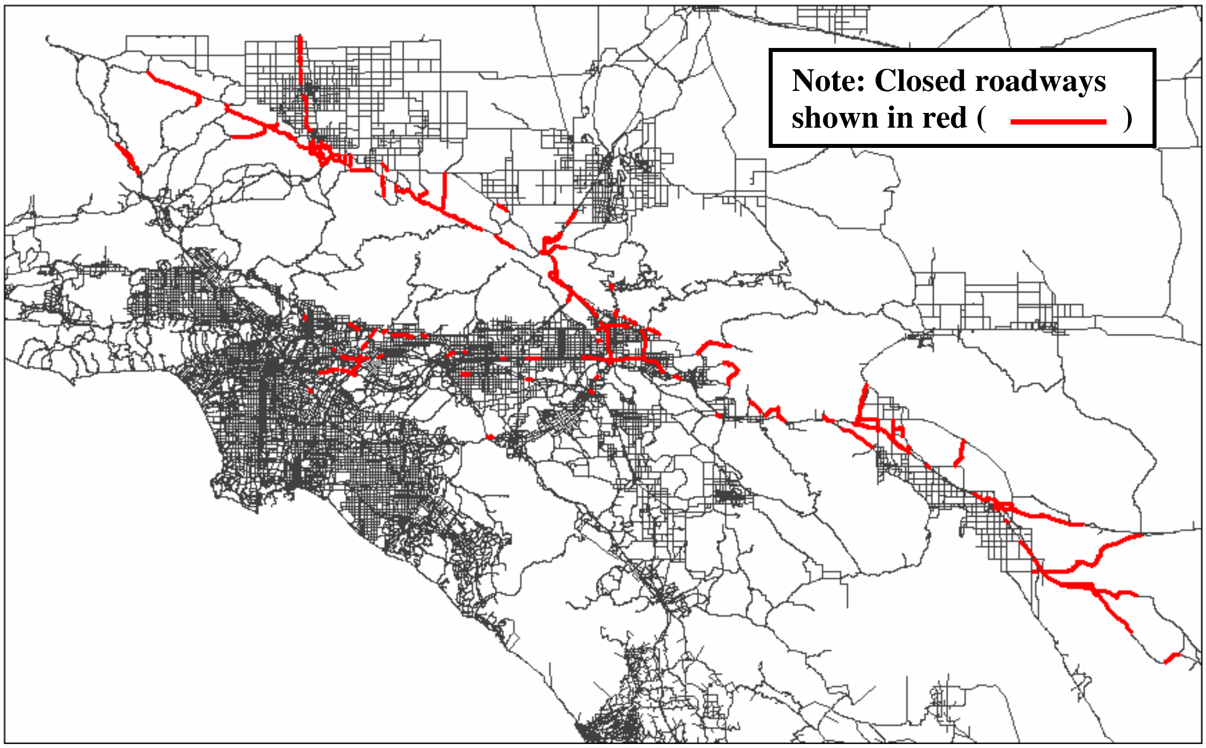


Figure 4-10. Closures at 12 Days after Earthquake (closures at this time are due to extensively and irreparably damaged bridges and irreparably damaged roadways)

- ***13-49 Days after Earthquake (Fig. 4-11).*** Within this time segment, all extensively damaged bridges have been reopened to traffic. The remaining closures are due to irreparably damaged bridges and roadways. Comparison of Figures 4-10 and 4-11 shows fewer roadway closures due to reopening of the extensively damaged bridges, but a similar spatial pattern of the remaining closures (with the notable exception that the previously closed segment of I-5 north of Los Angeles which has been reopened).

- ***50-140 Days after Earthquake (Fig. 4-12).*** By the beginning of this post-earthquake time segment, the many irreparably damaged roadways in the vicinity of the fault rupture have been replaced and reopened to traffic. The closures that remain are due to the irreparably damaged bridges in the study area. Thus, travel into the Los Angeles area from the east, which had been largely cut off due to the many closed roadways in the fault rupture area are now open, although with some detours around the segments of I-10 where irreparably damaged bridges are being replaced are still closed.

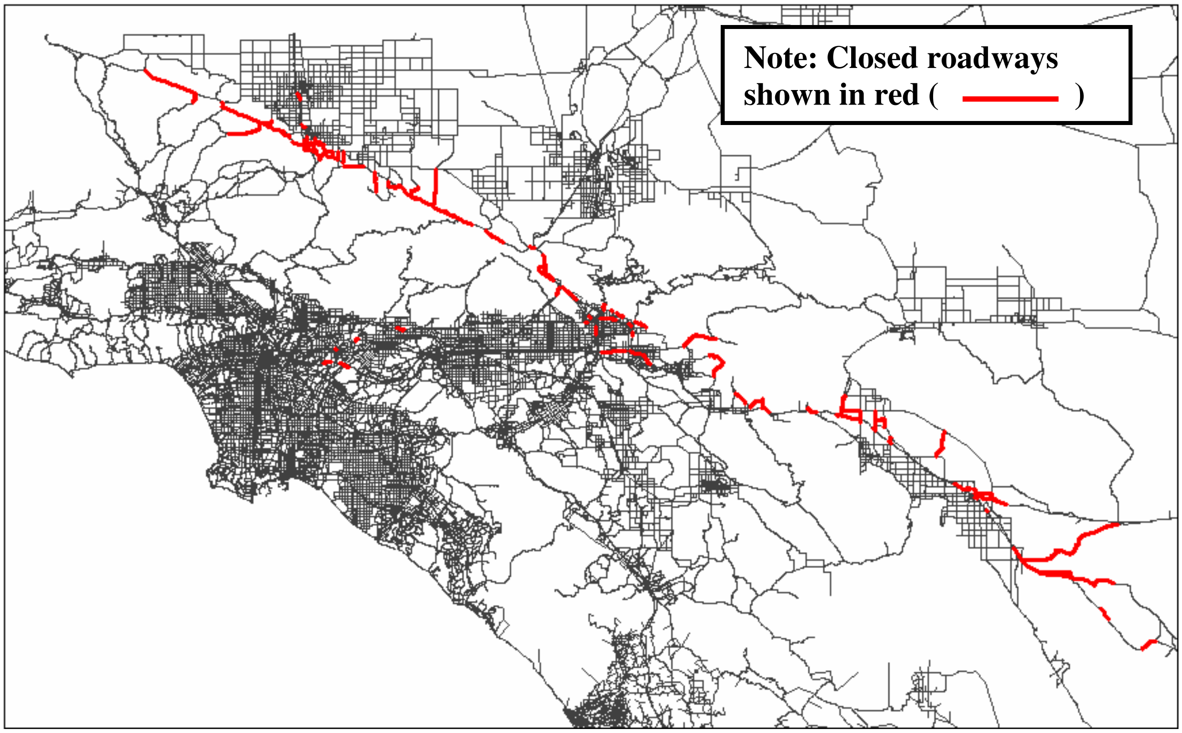


Figure 4-11. Closures at 13-49 Days after Earthquake (closures at this time are due to irreparably damaged bridges and roadways)

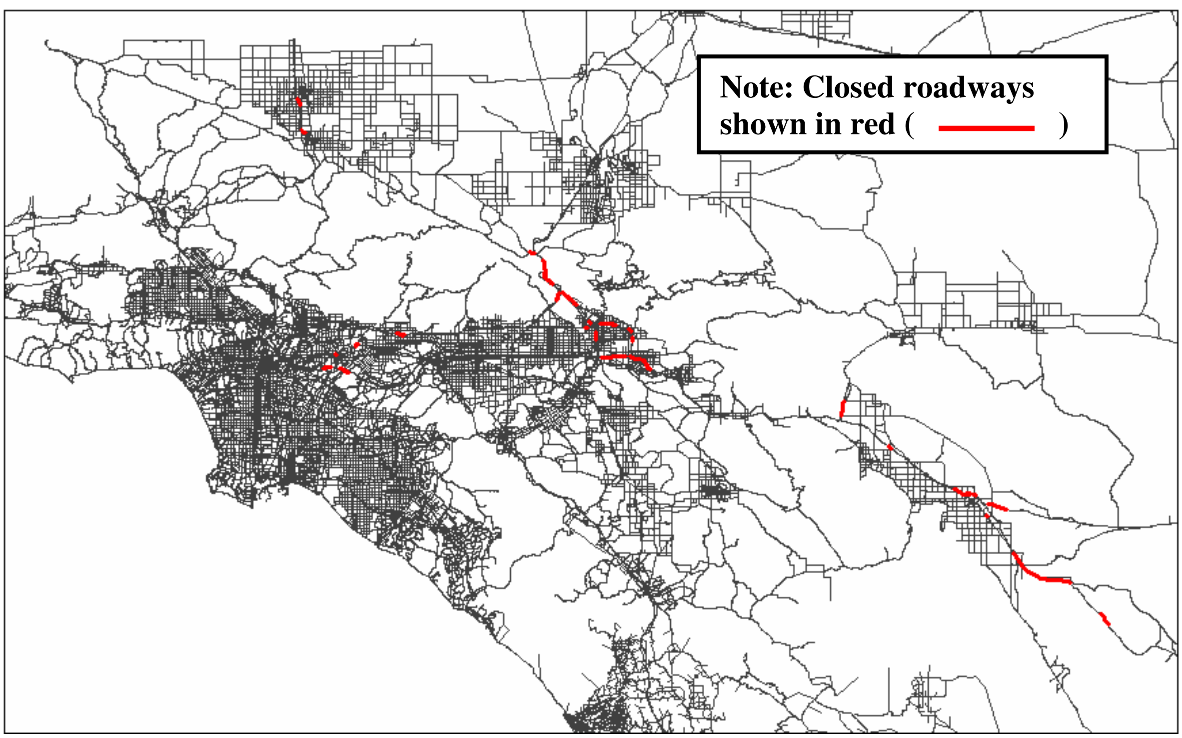


Figure 4-12. Closures at 50-140 Days after Earthquake (closures at this time are due to irreparably damaged bridges)

- ***System State at 221 Days after Earthquake (Fig. 4-13).*** Over the time periods from 141 to 220 days after the earthquake, replacement of all irreparably damaged bridges is being completed. According to our repair model, this work will be completed and all roadways in the study area will have been reopened to traffic at a post-earthquake time of 221 days.

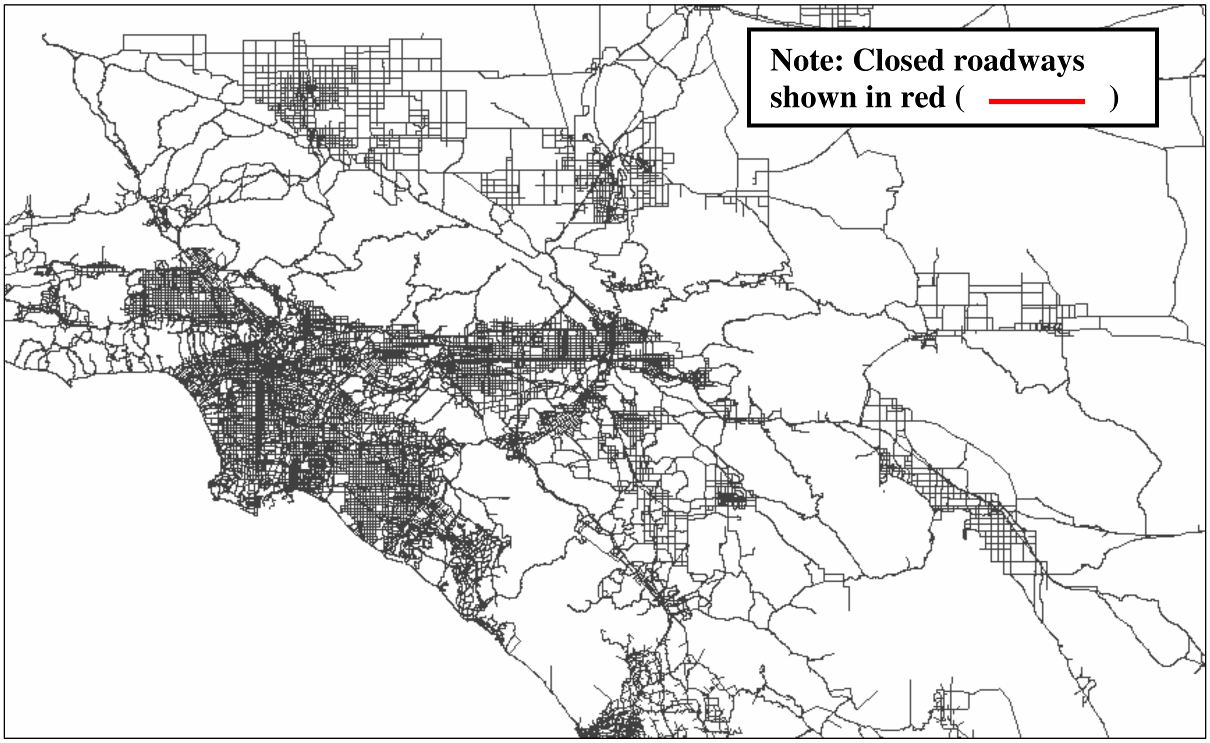


Figure 4-13. System State at 221 Days after Earthquake (which is the first day after the earthquake when all repairs have been completed and all roads are open to traffic)

All of the above system states and their post-earthquake occurrence times are based on the default repair models that are described in Section 2.3.2. The various model assumptions that are discussed in that section should be kept in mind when interpreting these results. Actual repair strategies and repair resources may differ from these assumptions, and this could lead to actual system states and associated post-earthquake times that differ substantially from those described above. This would also affect the estimated traffic impacts and associated economic losses that are summarized in the following section of this chapter. For this reason, additional analyses of the effects of these repair alternatives on the results of this SRA are recommended in Section 5.2.

4.4 REGION-WIDE TRAVEL IMPACTS

Using the highway-network and trip table data described in Chapter 3, the REDARS™ 2 network analysis procedure that is summarized in Section 2.3.3 was applied to each of the above system states. This analysis led to estimated traffic flows and travel times associated with each system state and their associated post-earthquake times of occurrence. The analysis also estimated how trip demands at each post-earthquake time were affected (reduced) by increased congestion due to the earthquake-induced roadway closures at each post-earthquake time.

Table 4-8 provides the end results of this analysis in terms of system-wide trip demands, travel times, and travel time per 24-hour day. These results have been developed for the highway system's baseline (pre-earthquake undamaged) system state and for each of the post-earthquake system states described in Section 4.3. They show the following trends:

- The post-earthquake system-wide trip demands system decrease relative to the pre-earthquake trip demands by relatively small factors that range from about 2.7 percent during the 0-3 day post-earthquake time period (before post-earthquake repairs have been initiated) to about 0.3 percent during the 50-140 post-earthquake time period (when all bridge and roadway repairs have been completed except for the irreparably damaged bridges).
- The post-earthquake system-wide travel times increase relative to the pre-earthquake travel times by factors ranging from nearly 18 percent during the 0-3 day post-earthquake time period to slightly less than 8 percent during the 50-140 day post-earthquake time period.
- The corresponding average system-wide travel time per trip increases by factors ranging from about 21 percent shortly after the earthquake to nearly 9 percent during the 50-140 day post-earthquake time period.

It is noted that all of the above percent-changes in region-wide trip demands and travel times are relative to the very large number of pre-earthquake trip demands and travel times throughout the Southern California region. Thus, the absolute values to these changes are very large numbers. This is reflected in the large economic losses due to highway-system damage that are provided in the following section of this chapter.

In addition to the above trip-demand and travel-time results, the network analysis has also estimated the increases in region-wide travel distance (in units of lane-miles traveled per day) associated with the various post-earthquake system states described in Section 4.3. These results showed that increases in travel distances relative to pre-earthquake travel distances that ranged from about 2 percent during the 0-3 day post-earthquake time period to less than 1 percent during the 50-140 day post-earthquake time period. These small percentages are relative to the very large number of region-wide lane-miles traveled per day throughout the region. Thus, the absolute value of the increases in distances traveled during the above post-earthquake times are still large numbers.

4.5 ECONOMIC LOSSES

The procedure described in Chapter 2 was used to estimate economic losses due to increased travel times and reduction in trip demands caused by the earthquake damage to the highway system. This estimate was based on the following considerations:

- As discussed in Chapter 3, it was not possible to utilize separate region-wide trip tables because of limitations in the available SCAG data and the very large size of the highway system that was analyzed.. Therefore, our network analysis assumed that all trips throughout the system are associated with the single (pre-earthquake) trip table for autos that was provided by SCAG.

Table 4-8. Network Analysis Results

System State	System-Wide Trips per Day *			System-Wide Travel Times per Day *			System-Wide Travel Time per Trip per Day *		
	Total (PCU)	Decrease from Pre-EQ (PCU)	Percent Decrease from Pre-EQ	System-Wide Travel Time (PCU)	Increase from Pre-EQ (PCU-hr)	Percent Increase from Pre-EQ	Average Travel Time per trip, (min.)	Increase from Pre-EQ (min.)	Percent Increase from Pre-EQ
Pre-EQ	23.784×10^6	0.0	0.0	19.575×10^6	0.0	0.0	49.4	0.0	0.0
0-3 days after EQ	23.152×10^6	6.320×10^5	-2.7	23.058×10^6	34.832×10^5	17.8	59.8	10.4	21.0
12 days after EQ	23.329×10^6	4.554×10^5	-1.9	22.503×10^6	29.277×10^5	15.0	57.9	8.5	17.2
13-49 days after EQ	23.475×10^6	3.086×10^5	-1.3	21.701×10^6	21.261×10^5	10.9	55.5	6.1	12.3
50-140 days after EQ	23.708×10^6	0.758×10^5	-0.3	21.068×10^6	14.924×10^5	7.6	53.2	3.9	8.0
221 days after EQ	23.784×10^6	0.000	0.0	19.575×10^6	0.0	0.0	49.4	0.0	0.0

* The baseline (pre-earthquake) trip demands and travel times provided in the SCAG data that was the basis of this network analysis (as described in Chapter 3) correspond to a three-hour peak-traffic time period extending from 6 AM to 9 AM. The SCAG data indicates that, to enable these trips and travel times to correspond to a 24-hour day, they should be multiplied by a factor of 4.44. Thus, in our network analysis, we have applied this factor to the baseline values of these parameters that have been obtained from SCAG.

- Two estimates of economic losses have been developed. The first (Case 1) assumes that all system-wide trips correspond to automobile trips only, and the second estimate assumes that about 6.5% of the system-wide trips correspond to truck trips and the remainder corresponds to automobile trips. This assumed percentage of truck trips was based on truck trip data for Southern California that was provided by SCAG. As noted in Chapter 2, the following economic loss estimates are based on unit losses of $13.45/hour for an auto trip (which corresponds to 1 PCU) and $71.05/hour for a truck trip (which corresponds to 3 PCU). As noted in Chapter 2, these unit losses are based on data for Southern California that were obtained from traffic-congestion statistics developed by the Rand Corporation of California (and obtained from their website, which is http://ca.rand.org).

Based on these assumptions, the unit economic losses per day associated with each system state are shown in Table 4-9.

Total economic losses due to travel time increases and trips foregone were obtained by plotting the unit losses per day vs. the post-earthquake time segment over which they occur. These plots are shown in Figure 4-14 for the Case 1 loss estimate. (Table 4-9 shows that the Case 2 loss estimate will lead to a very similar plot). The variations of unit losses over time that are shown in this figure are consistent with the repair milestones estimated by the bridge and roadway repair models shown in Tables 2-4 and 2-6. Based on these models, the unit losses within the 0-3 day, 13-49 day, and 50-140 day time segments that are listed in Table 4-9 are assumed to be constant. The unit losses within the 4-12 day and 141-221 day post-earthquake times are assumed to be linearly varying, in order to approximate effects of intermediate repair milestones within these time segments that are estimated by the repair models.

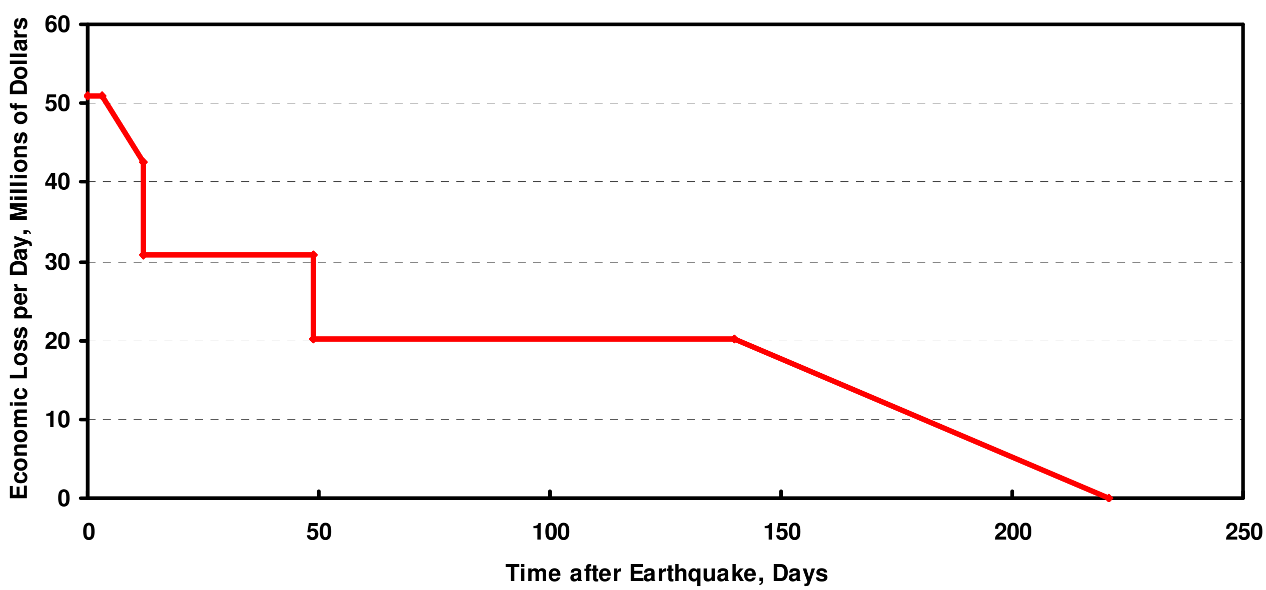


Figure 4-9. Economic Losses per Day due to Region-wide Travel Time Delays and Trips Foregone

Table 4-9 Economic Losses/Day due to Travel Time Delays and Trips Foregone

Post-EQ System State	(A) Travel Time Increase over Pre-EQ Travel Time, (PCU-Hours)	Trip Demand Decrease		(D) Economic Loss/Day (Millions of Dollars)	
		(B) Relative to Pre-EQ Trip Demand (PCU)	(C) Equivalent Travel Time Increase (PCU-Hours)	Case1. 100 percent of Trips =Auto (= $13.45 x (A+C))*	Case 2. 93.5% of Trips = Auto and 6.5% of Trips = Truck (= $14.12 x (A+C))**
0-3 days after EQ	34.832×10^5	6.320×10^5	3.063×10^5	$50.97	$53.52
12 days after EQ	29.277×10^5	4.554×10^5	2.429×10^5	$42.64	$44.78
13-49 days after EQ	21.261×10^5	3.086×10^5	1.608×10^5	$30.76	$32.30
50-140 days after EQ	14.924×10^5	0.758×10^5	0.060×10^5	$20.15	$21.16
221 days after EQ	0.0	0.000	0	$0.00	$0.00

Note:

* $13.45 = Estimated dollar value of 1 hour of travel via automobile (1 PCU)

** $14.12 = $13.45 (value of 1hour of 1 PCU) * 0.9343 (Auto trip ratio)
+ [$71.05 (value of 1 hour of a Truck) / 3 PCU (Truck to PCU)]* 0.0657 (truck trip ratio)

The total economic losses are shown in Table 4-10 for the Case 1 and Case 2 loss estimates as the sum of the losses due to travel time delays and trips forgone plus the repair costs. The losses due to travel time delays and trips foregone have been computed as the area enclosed by the unit loss vs. time plot shown in Figure 4-9, and the repair costs are based on the unit costs included in the bridge and roadway repair models and shown in Tables 2-5 and 2-6 . Table 4-10 shows total losses of about $4.8 billion for Case 1 and about $5.0 billion for Case 2. These are dominated by the losses associated with travel time delays and trips foregone; i.e., the repair costs constitute only a small fraction of the total losses for these cases.

Table 4-10. Economic Loss Estimates

Loss	Case 1. 100% of Trips are Automobile	Case 2. 93.5% of Trips = Auto and 6.5% of Trips = Truck
Due to Travel Time Delays and Trips Foregone	$4.33 billion	$4.55 billion
Repair Costs	$0.43 billion	$0.43 billion
Total	$4.76 billion	$4.98 billion

As points of reference for assessing these results, Caltrans has previously estimated the total losses of about $217 million due to highway system damage caused by the Northridge Earthquake (Cho et al., 2006b). In addition, a recent study has estimated losses of about $744 million due to possible traffic disruptions caused by tsunami-induced inundation (Borrero et. al, 2005). The overall cost to repair or replace bridges damaged during Hurricane Katrina is estimated at over $1 billion (Padgett et al., 2008). The additional losses due to travel time delays and trips foregone are most probably well in excess of these repair/replacement costs. Thus, the losses shown in Table 4-10 are much larger than the losses from the Northridge Earthquake and the tsunami damage estimates, but are at least on the order of and probably much less than losses from Hurricane Katrina.

CHAPTER 5
CONCLUDING COMMENTS

5.1 PROJECT SUMMARY

This project has conducted an analysis of the seismic risks to the SC highway system due to the Magnitude 7.8 earthquake scenario along the southern San Andreas Fault that is being considered under this Golden Guardian (GG) exercise. This analysis has been carried out by applying REDARS™ 2, which is a new multidisciplinary and modular methodology and software package for SRA of highway systems nationwide. REDARS™ 2, whose development has been supported under multi-year Federal Highway Administration and Caltrans research projects, represents the state of the art for such SRA applications. It can be used to carry out deterministic or probabilistic SRA of highway systems nationwide that include estimation of site-specific ground shaking and ground displacement hazards, component damage states and repair requirements due to these hazards, post-earthquake traffic flows, travel times, and trip demands that are affected by closures of various links in the system while damaged components along these links are being repaired, and economic losses due to travel time delays and reduced trip demands caused by these link closures. However, the scope of this project has been limited to one single deterministic SRA of the SC highway system, and has excluded sensitivity analyses of effects of model or input-data uncertainties on the SRA results. Results from this analysis are summarized below.

- ***Effects of Ground Shaking Hazards.*** Analysis of potential bridge damage due to ground shaking was based on the REDARS™ 2 default bridge model and the NBI and Caltrans input data that are described in Chapters 2 and 4. This analysis showed that many of the bridges located in the vicinity of the fault rupture where estimated ground motions are very high could undergo severe damage. This includes bridges along freeways and roadways in the vicinity of Indio, San Gorgonio Pass and Palm Springs, San Bernadino and Cajon Pass, and Palmdale. These results also showed additional smaller pockets of severely damaged bridges at locations within the Los Angeles basin near Baldwin Park and Monterey Park, where localized substantial amplifications of ground motions have been predicted by USGS. About 90% of the severely damaged bridges in these areas: (a) were older structures designed and constructed prior to 1975, using only minimal seismic design procedures that were in place at that time; and (b) had not undergone a Phase 2 retrofit. More recently designed bridges and bridges that had undergone a Phase 2 retrofit were estimated to generally perform much better than the older unretrofitted bridges; only about 10 percent of the severely damaged bridges fell in this category.
- ***Effects of PGD Hazards.*** This analysis also estimated the potential for highway damage due to: (a) fault rupture, landslides at the Cajon Pass and San Gorgonio Pass; and (b) liquefaction in the Coachella Valley and the San Gorgonio Pass. Roadway PGDs due to surface fault rupture were very large, with values of up to 7.2 m. in the Coachella Valley, 6.7 m. at the San Gorgonio Pass, 1.1 m. at the Cajon Pass, and 3.0 m. near Palmdale. REDARS™ 2 default highway damage state models estimated that such PGDs will cause severe damage to all roadways subjected to such fault-rupture displacements. Severe highway damage was also estimated to occur from liquefaction and landslides in the Cajon Pass and San Gorgonio Pass areas, along with roadway blockage due to landslides in these areas.

- ***Damage Repair Estimates***. REDARS™ 2 default repair models were used to estimate repair costs and downtimes due to the bridge and highway damage summarized above. These models were previously developed in collaboration with senior Caltrans staff for repairs under non-emergency conditions only, and included the following simplifying assumptions: (a) all repair resources needed for all of the damaged bridges throughout the study area will be readily available and can be rapidly mobilized at all of the damaged bridge and highway sites; (b) all bridge damage will be readily accessible for repairs; (c) emergency measures for accelerating repairs at major freeways (e.g., issuance of bonus-incentive contracts) are not considered. Using these assumptions, the models estimated that repair of severely damaged *bridges* could require downtimes and associated complete closures to traffic for time durations ranging from about 5-7 months. Downtimes and completed closures of traffic during repair/replacement of severely damaged *roadways* were estimated to require approximately 7 weeks. Section 5.2 further discusses the above repair-model assumptions on which these downtime estimates are based. It is noted that these default repair models can be easily overridden by REDARS™ 2 users, if desired. However, effects of alternative repair models on SRA results could not be assessed within the limited scope of this project.

- ***Traffic Disruptions.*** Downtimes estimated by the REDARS™ 2 default repair model were used to form a series of post-earthquake system states at four different post-earthquake times. These system states differ from pre-earthquake system states in that, now, certain roadway links are closed for repair of earthquake damage.. Then, the REDARS™ 2 network analysis procedure was applied to each system state, in order to estimate region-wide traffic flows, travel times, and trip demands at each post-earthquake time and how they are affected by increased traffic congestion due to earthquake damage. Results from this analysis indicated that, at times shortly after the earthquake, region-wide travel times were increased by about 18 percent, while region-wide trip demands were decreased by only a few percent. As the time after the earthquake increased and various damaged links began to be reopened as their repairs were completed, these region-wide travel times and trip demands tend to approach their pre-earthquake values.

- ***Economic Losses***. Economic losses due to the above travel time increases and trip demand decreases were estimated. These estimates indicated very high economic losses that substantially exceeded previously estimated losses due to damage to the highway system that was caused by the Northridge Earthquake. However, these very high losses could be very sensitive to uncertainties in the various models used to estimated bridge and roadway damage states and repair times, as discussed in Section 5.2 below.

5.2 INTERPRETATIONS AND RECOMMENDATIONS

5.2.1 Bridge Damage States

5.2.1.1 Model

In accordance with the limited scope of this project as summarized above, analysis of potential bridge damage due to ground shaking was based on simple models that used bridge attribute data from the FHWA National Bridge Inventory (NBI) database which was developed to support bridge maintenance nationwide. This database was not intended to support seismic analyses and therefore does not include all of the bridge structural attributes that would ordinarily be needed to carry out such analyses. Therefore, as noted in Chapter 4, bridge analyses using this model and database should be viewed as an initial screening for identifying possible pockets of bridge damage, and are not intended to be a substitute for analyses using more detailed bridge models and additional bridge-specific structural attribute data. It is noted that REDARS™ 2 can readily accommodate such detailed user-specified bridge models; however, it was not possible to develop and apply such models within the scope of this project.

5.2.1.2 Input Data

As noted in Chapter 4, Caltrans bridge data indicates that many bridges near the fault rupture had been designed prior to mid 1970s (when only minimal seismic design procedures were in place) and had not undergone a Phase 2 retrofit. These data should be carefully checked, since our analysis showed that most of the very severe damage and associated extensive downtimes occurred at such bridges. If it turns out that many of these older bridges have indeed undergone a Phase 2 retrofit or other type of structural upgrade to improve seismic performance, it is likely that the extent of their damage (and associated roadway closures) would be reduced relative to the current predictions described in this report. This improved performance would also reduce the region-wide traffic disruptions and associated economic losses relative to current predictions.

5.2.1.3 Recommendations

Although based on a simplified bridge damage model and the limited bridge attribute data that we were able to consider, we believe that, as an initial estimate, it is plausible that older (pre-1975) bridges that have not undergone a Phase 2 retrofit and are located very near the fault rupture from a very large earthquake could be prone to severe damage as estimated from this analysis. However, these results should clearly be further checked through more detailed analysis of the seismic response of bridges throughout the SC study area, and especially near the ruptured fault for this scenario earthquake where most of the bridges estimated to undergo very severe damage are located. As noted above, we also recommend careful checking of the bridge attribute input data, particularly for those bridges that the current input data shows to be relatively old (pre-1975 design) and without a Phase 2 retrofit. .

In these more detailed analyses, it is very important to consider features of near-fault ground motions that could have an important effect on bridge response. Data from past earthquakes, such as the 1999 Chi Chi earthquake in Taiwan, have shown that near-fault ground motions will differ from ordinary ground motions in that they often contain strong coherent long period pulses. They are caused by rupture directivity effects and can lead to a high demand for energy absorption. This is especially true for high intensities of ground motion that drive structures into the non-linear range. If they are not considered during seismic design or upgrade, they can have a detrimental effect on the seismic performance of all near-fault bridges, and especially older and unretrofitted bridges whose seismic performance may already be borderline because of its minimal seismic design. In recognition of the importance of such near-fault ground motion characteristics, forthcoming FHWA-sponsored research will be investigating the seismic response and fragility modeling of near-fault bridges (Buckle, 2008).

5.2.2 <u>Bridge and Highway Repairs</u>

5.2.2.1 Models

Section 5.1 and earlier chapters of this report have summarized the assumptions on which that are the basis of the REDARS™ 2 default repair models for bridges and highways that have been used in this analysis. However, these assumptions may not lead to realistic estimates of bridge and highway repair costs and downtimes. For example, it is reasonable to assume that emergency repairs measures would most probably be used to accelerate bridge and roadway repairs along major freeways (e.g., I-10 and I-15). Such repair measures are not considered in the REDARS™ 2 default repair models. In addition, it is possible that, for at least a short time after the earthquake, delays in mobilizing repairs along many of the severely damaged bridges and roadways, due to widespread damage to all elements of the built infrastructure and the possible inability of immediately available repair resources to accommodate all of these many repair demands. This possibility is also not considered in the REDARS™ 2 repair models.

5.2.2.2 Recommendation

We believe that the REDARS™ 2 estimates of post-earthquake traffic impacts and associated economic losses could be very sensitive to the above repair-model assumptions. We therefore strongly recommend that sensitivity analyses be carried out that illustrate how such traffic impacts and economic losses could be affected by the above assumptions. In view of the limited scope of this project (as summarized in Section 5.1.1), such sensitivity analyses could not be included within the project's current time and budget.

5.2.3 <u>Highway and Trip Demand Input Data</u>

A cornerstone of the REDARS™ 2 variable-demand network analysis procedure is the relationship between trip demands and congested travel time that is illustrated in Figure 2-6 of Chapter 2. Under this project, this relationship has been developed from calibrations against SCAG and SANDAG trip-distribution and travel-time data under normal operating conditions. However, this calibrated relationship may not fully represent trip reductions for a severely damaged system such as the system analyzed under this project. To assess the effects of uncertainties in this relationship, we recommend that reasonable bounds on rates of change of trip demands as a function of congested travel time be estimated from expert opinion, and that sensitivity analyses then be carried out to indicate how these uncertainties may affect computed post-earthquake traffic flows, travel times, trip demands, and associated economic losses.

5.2.4 <u>Other Recommendations</u>

Although not directly related to our project, we provide the following recommendations that we believe would help to clarify the potential consequences of the GG scenario earthquake on all elements of the built infrastructure that could be affected by this earthquake:

- It is likely that many elements of the SC built infrastructure could be damaged by the very large scenario earthquake considered in this GG exercise. However, from the viewpoint of infrastructure decision-makers, the extent of (and funding for) any seismic risk reduction measures implemented in response to the results of this exercise will likely depend upon the likelihood of occurrence of such an earthquake over some further exposure times. For example, if such an earthquake was estimated to be highly likely over these exposure times, the urgency of implementing appropriate risk-reduction measures would be increased.

- In this scenario earthquake, the fault rupture stops short of I-5 in the Tejon Pass area, which is the major interstate trucking route into and out of the greater Los Angeles area from the north. If the rupture were to extend for a slightly longer distance and cross I-5, economic losses due to earthquake damage to the SC highway system would be considerably greater. Therefore, we suggest that, at some stage (perhaps as a future extension of this GG exercise) an earthquake event whose fault rupture extends across I-5 north of Los Angeles as well as I-10 and I-15 east of Los Angeles be considered.

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